Don’t confuse invested resources reduction with productivity, or productivity with value delivery: an indoor air case study

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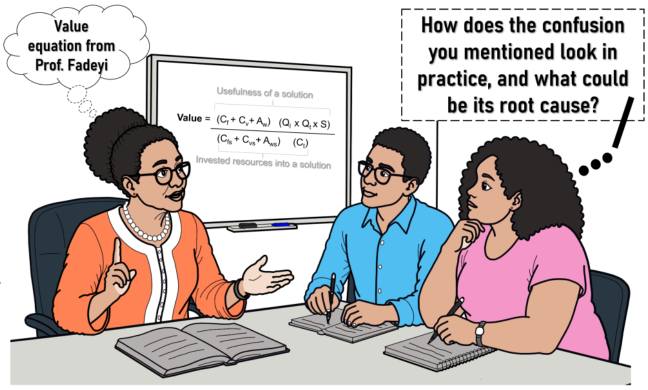
DON'T CONFUSE INVESTED RESOURCES REDUCTION WITH PRODUCTIVITY, OR PRODUCTIVITY WITH VALUE DELIVERY: AN INDOOR AIR CASE STUDY

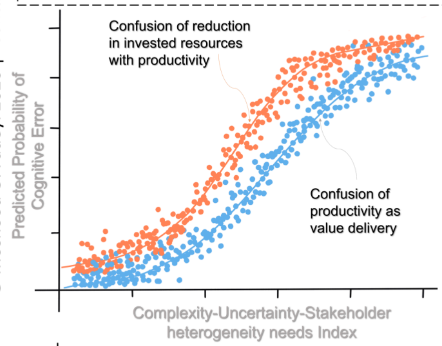


Consider this case. A facility management team introduced AI to streamline indoor air management. Data collection, reporting, and scheduling became faster, and time and financial resources were significantly reduced. Based on this, the FM claimed improved productivity. However, what was actually improved was the efficiency of process execution, not the effectiveness of exposure control. Ventilation adequacy, pollutant interactions, and occupant-specific risks were not interrogated. So, resource reduction was misclassified as productivity.

*AI means artificial intelligence

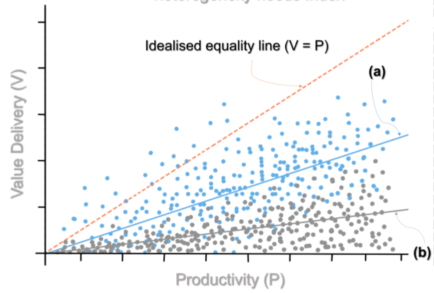
Where: Quality (Q_t), Quantity (Q_l), Safety level (S), i.e. the extent to which the risk of human death is reduced; Comfort (C_f); Convenience (C_v); Awareness (A_w), i.e. the level of cognitive clarity and certainty gained; Sacrificed Comfort (C_{fs}), Convenience (C_{vs}), and Awareness (A_{ws}); and Costs (C_t), in terms of time and financial resources. Note that the value equation presented here reflects the consumer perspective. The specific value equation for producers is presented in Fadeyi (Dec. 2024).

In another instance, management began tracking output quality superficially, such as compliance scores or number of issues resolved. The productivity ratio increased, and this was interpreted as value delivery. Yet indicators of healthy living, such as comfort, cognitive clarity, and symptom reduction, did not improve. More importantly, the functional outcomes of occupants, including their ability to concentrate, make decisions, and perform tasks effectively, also showed no meaningful improvement.



Confusion becomes costly as cognitive errors increase with the real-life problem index.

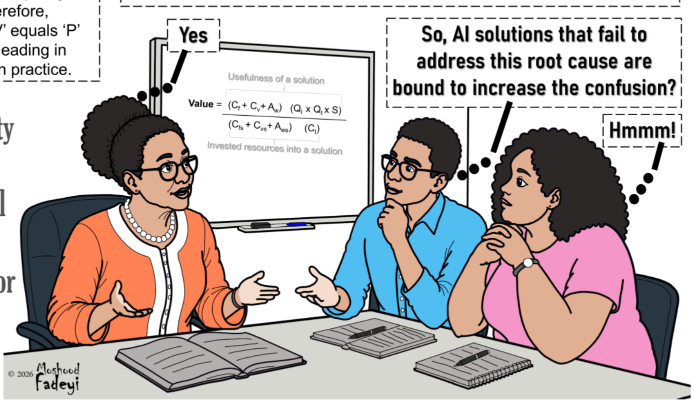
(**a**) This line represents the case where a reduction in invested resources is not confused with productivity. In practice, there is a significant deviation from the idealised equality line (V = P); therefore, 'V' should not be assumed to equal 'P'.



(**b**) This line represents the case where a reduction in invested resources is confused with productivity. In practice, this leads to a greater deviation from the idealised equality line (V = P). Therefore, assuming 'V' equals 'P' is more misleading in this common practice.

Note: Productivity = Output / Invested resources. Invested resources, also referred to as input, include only Costs (C_t), in terms of time and financial resources. In practice, C_{fs}, C_{vs}, and A_{ws} are not treated as part of these resources. Output is defined primarily in terms of total quantity produced. Quality and safety are intended to act as constraints on output quantity. However, they are often weakly enforced or decoupled from productivity measurement, allowing output quantity to increase and productivity to appear higher, even as quality and safety deteriorate. Additionally, the effects of output on stakeholders, in terms of C_f, C_v, and A_w, are not considered in productivity measurement.

As complexity, uncertainty, and stakeholder heterogeneity increase, these misjudgements intensify. The system appears efficient, but it systematically fails to deliver real value. The lack of cognitive capability enhancement to support sound judgement, decision-making, and action for value-oriented problem diagnosis and solving is the root cause of this confusion and should be addressed.



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Fictional Case Story (Audio – available online)– Part 1 (Preface, Ch 1 & Ch 2)

Fictional Case Story (Audio – available online) – Part 2 (Ch 3)

Fictional Case Story (Audio – available online) – Part 3 (Ch 3 cont'd)

Fictional Case Story (Audio – available online) – Part 4 (Ch 4)

Fictional Case Story (Audio – available online) – Part 5 (Ch 4 cont'd)

Fictional Case Story (Audio – available online) – Part 6 (Ch 5 & Ch 6)

………………… Preface ……………………

In a world increasingly celebrated for intelligent technologies, sustainable infrastructure, and operational optimisation, buildings became more advanced while human beings quietly became more exhausted. Organisations proudly displayed energy-saving achievements, automation capabilities, productivity improvements, and environmental performance indicators, yet many people continued experiencing fatigue, anxiety, cognitive exhaustion, emotional disconnection, and declining wellbeing within the very systems designed to improve human life.

Within indoor air management practice especially, ventilation systems, airflow strategies, filtration technologies, and intelligent environmental controls increasingly focused on measurable operational performance while the lived experiences of occupants often remained insufficiently understood. Under growing uncertainty, complexity, competing stakeholder pressures, and operational demands, societies increasingly gravitated toward whatever appeared most measurable, defensible, and psychologically reassuring. As a result, visible optimisation often became confused with genuine human progress.

Intelligent systems improved efficiency, accelerated operational performance, and reduced invested resources, yet the deeper human consequences unfolding beneath those systems frequently remained overlooked. Consequently, reductions in invested resources were increasingly mistaken for productivity improvement, while productivity improvement itself was increasingly mistaken for proportional improvement in genuine human value delivery, even when the lived experiences of people quietly deteriorated underneath. This revealed a quiet but pervasive cognitive flaw shaping modern judgement, decision-making, and problem-solving across both professional and personal life.

A young engineering student, disturbed by the growing contradiction between operational optimisation and human wellbeing, gradually embarked on a lifelong journey involving love, loss, uncertainty, family, research, and personal transformation. In confronting the flaw shaping modern systems, she would eventually be forced to confront similar tendencies within herself. Her journey forms the subject of this fiction story.

………………… Chapter 1 ……………………

Amina Awotade was born into a society that looked successful from the outside but was quietly exhausting the people living inside it. From childhood, she grew up surrounded by images of progress so dazzling that questioning them almost felt irrational. Every night, the city transformed into a glowing landscape of glass towers, moving lights, digital screens, and endless streams of traffic flowing beneath elevated expressways.

The skyline glittered with impossible beauty. Towering skyscrapers reflected rivers of white and gold across the dark sky while giant digital billboards celebrated innovation, productivity, efficiency, and economic growth.Advertisements displayed smiling professionals walking confidently through futuristic offices while slogans promised optimisation, acceleration, and limitless potential. The entire city seemed designed to convince people that society was moving successfully toward a better future.

Politicians proudly described the country as one of the most competitive economies in the world. News channels constantly praised companies that reduced costs, accelerated implementation, increased operational efficiency, and achieved stronger productivity growth under uncertain global economic conditions.

Even ordinary conversations gradually became filled with the language of optimisation. Parents discussed productivity targets at dinner tables. University students are constantly worried about employability and competitiveness.

Employers praised workers who could multitask under pressure, respond rapidly to uncertainty, and maintain performance under increasingly demanding conditions. Success itself increasingly became associated with the ability to function continuously without slowing down emotionally or cognitively.

Everywhere Amina looked, society appeared obsessed with measurable performance. Unlike many people around her, Amina had always been unusually observant.

Even as a child, she noticed small emotional details others ignored. She noticed how adults smiled politely while looking exhausted underneath. She noticed how students celebrated achievement while quietly breaking down emotionally. She noticed how people increasingly spoke the language of optimisation, productivity, and efficiency while becoming progressively less emotionally present with one another. Although she could not yet fully explain these contradictions, the patterns stayed inside her mind for years.

As she grew older, however, she began noticing something strange. Despite all the operational success surrounding her, people looked increasingly emotionally drained. Teachers became exhausted. Office workers stared silently inside crowded trains every morning.

Her father returned home mentally depleted almost every night, even though his engineering company constantly celebrated productivity improvement and operational excellence. Her mother, who worked in healthcare administration, increasingly complained that hospitals had become “efficient but emotionally empty.” Everything in society seemed to move faster every year, yet life somehow felt heavier.

Amina noticed it most during her daily train journeys to university. Every morning, thousands of people packed themselves silently into crowded train compartments beneath harsh fluorescent lighting. Faces glowed faintly from phone screens while exhaustion hung invisibly in the air like humidity before a storm. Nobody spoke much anymore. People simply scrolled endlessly through emails, financial updates, productivity applications, performance notifications, and meeting schedules before the workday had even begun. Sometimes Amina wondered whether the entire city had quietly become emotionally tired without fully realising it.

At first, Amina believed the problem was simply stress. University life was demanding, companies were highly competitive, and modern cities moved at exhausting speed. Those explanations initially seemed sufficient to her. However, as she continued observing people around her more carefully over several years, certain patterns began disturbing her emotionally.

The same emotional exhaustion appeared repeatedly across very different environments. Students became mentally drained despite achieving impressive academic performance. Office workers looked increasingly exhausted even when companies celebrated productivity improvement and operational success. Hospitals became more operationally efficient while healthcare workers and patients increasingly complained about emotional detachment and fatigue.

What unsettled Amina most was not the existence of stress itself, but the strange contradiction surrounding it. Society constantly celebrated optimisation, efficiency, acceleration, and performance improvement, yet many people seemed increasingly overwhelmed emotionally and cognitively.

The contradiction became difficult for her to ignore because the same pattern kept appearing repeatedly in schools, workplaces, transportation systems, hospitals, and even inside her own family. The more society focused on visible operational success, the more emotionally exhausted many people seemed to become underneath that success.

However, as she observed the world more carefully, she realised something far more disturbing was happening. Under uncertainty, pressure, and competition, society itself had gradually developed a dangerous cognitive flaw.

People increasingly struggled to think deeply under pressure. As they struggled to think deeply, they became increasingly confused whenever situations involved uncertainty, complexity, delayed consequences, and heterogeneous human needs.

As a result, society increasingly prioritised visible operational indicators because those indicators were easier to measure, easier to interpret, and emotionally reassuring under uncertain conditions.

The deeper Amina reflected upon the issue, the more she noticed how society increasingly rewarded cognitive simplification under pressure. Leaders who delivered rapid, visible outcomes were celebrated more easily than those who carefully navigated complexity.

Companies preferred measurable short-term operational success because uncertainty surrounding long-term human consequences made investors uncomfortable. Institutions increasingly valued visible movement because visible movement created psychological reassurance.

Under pressure, society itself seemed to emotionally gravitate toward measurable indicators the same way frightened people instinctively search for stable ground during an earthquake.

The consequences appeared everywhere. Schools optimised measurable academic performance while students quietly suffered emotional burnout, severe anxiety, emotional breakdowns, and worsening psychological deterioration, with many parents left struggling to manage the consequences and sometimes unfairly blamed for them.

Companies celebrated productivity growth while workers developed chronic fatigue, anxiety, and cognitive exhaustion. Buildings became more energy efficient while occupants increasingly complained about headaches, discomfort, poor concentration, and respiratory irritation.

Yet every time hidden human consequences emerged, society responded in the same way: more optimisation, more operational efficiency, and more measurable performance indicators. It was as though society had become psychologically dependent on visible operational success because visible indicators reduced uncertainty emotionally.

During her second year at university, one of Amina’s classmates collapsed during a group presentation after spending several consecutive nights working without proper sleep. The incident shocked students briefly, but within days, the university resumed functioning normally as though emotional breakdown had become an expected side effect of achievement.

Counselling emails were distributed. Faculty members encouraged “better stress management.” Yet nobody seriously questioned whether the environment itself had become psychologically unhealthy. The system simply absorbed the damage and continued moving forward.

Amina saw the damage personally inside her own family. Her father worked for a multinational engineering corporation that underwent constant restructuring because of increasing global economic competition. Every year brought new optimisation initiatives, labour reduction strategies, operational redesign programmes, and performance acceleration targets.

One evening, when Amina was nineteen and in her first year at university, she woke up late at night and found her father sitting alone in the darkness at the dining table. His laptop screen illuminated his face faintly while financial spreadsheets glowed across the screen. He looked emotionally broken.

Outside the apartment windows, the city still pulsed with movement despite the late hour. Aircraft lights moved silently across the night sky while distant office towers remained brightly illuminated long after midnight. Somewhere below, traffic continued flowing endlessly through the streets as though the city itself no longer knew how to rest.

Inside the apartment, however, everything felt painfully still. Amina could hear the soft mechanical hum of the refrigerator and the occasional tapping of her father’s fingers against the dining table. The silence between those sounds felt unbearably heavy.

Earlier that evening, his company had announced another major restructuring exercise. Entire departments would be merged, productivity targets increased, and staff numbers reduced again.

For several minutes, he simply stared silently at the spreadsheets before finally whispering something Amina never forgot. He said, “We keep becoming more efficient, but nobody asks what this efficiency is doing to people.” That sentence remained inside her mind for years because it captured something she had already begun sensing but could not yet fully explain.

At twenty-three, during the final year of her architectural engineering degree, Amina witnessed the flaw damage someone she cared deeply about. Her close friend Daniel was one of the few people she knew who constantly questioned assumptions. Unlike most students, he disliked reducing human problems into operational variables and measurable indicators.

Together, they participated in a prestigious international university engineering innovation competition focused on designing future-ready sustainable learning environments. The competition was heavily promoted across universities as one of the most important student engineering events in the region.

The winning team would receive a prize valued at nearly two hundred thousand dollars, together with industry sponsorship opportunities, international media recognition, research funding support, and direct recruitment consideration from several multinational engineering companies. Many students, therefore, viewed the competition not merely as an extracurricular activity but as a rare opportunity capable of significantly influencing their future careers.

The competition challenged student teams to develop small proof-of-concept classroom solutions capable of reducing energy consumption and improving operational efficiency within educational spaces. Most teams constructed temporary enclosed learning booths approximately the size of a small study room, large enough to accommodate two to four occupants performing simulated learning activities under controlled environmental conditions.

For many students, the competition represented far more than academic prestige alone. Some hoped the prize money could support their families financially. Others saw the competition as a pathway toward social recognition, financial stability, startup opportunities, or escape from economic uncertainty in an increasingly competitive society. The emotional pressure surrounding the competition, therefore, became enormous long before the final demonstration phase even began.

The competition consumed their lives for nearly eight months. Students slept inside laboratories, skipped meals, and survived on coffee, instant noodles, and adrenaline while racing toward impossible deadlines. Corporate sponsors visited frequently, reminding participants that future engineering solutions needed to remain commercially scalable, operationally efficient, and financially competitive under uncertain economic conditions.

Gradually, the atmosphere inside the engineering faculty became emotionally suffocating. Conversations increasingly revolved around implementation feasibility, optimisation metrics, energy targets, maintenance simplicity, and performance modelling, while deeper discussions about occupant wellbeing, long-term human consequences, and the lived experiences of future users slowly disappeared beneath operational urgency.

As the competition intensified, the students gradually became consumed by deadlines, sponsor expectations, performance metrics, and implementation feasibility requirements. Corporate representatives repeatedly reminded participants that future engineering solutions needed to remain commercially scalable, financially competitive, operationally efficient, and rapidly implementable under uncertain economic conditions.

Students quickly realised that projects demonstrating visible optimisation and measurable operational performance received the strongest praise and attention from judges and sponsors. Gradually, many teams began narrowing their thinking toward whatever appeared most measurable, defensible, and operationally convincing under pressure. Human complexity slowly became secondary to operational optimisation.

Daniel became increasingly disturbed by what he observed. One evening, after another exhausting design review session, he quietly said, “We are learning how to optimise systems, but not how to protect people from the consequences of optimisation.”

Most students ignored him. Some students laughed awkwardly because Daniel’s comments sounded emotionally uncomfortable within such a competitive environment. Others dismissed him as overly philosophical. A few privately agreed with him but remained silent because questioning the system itself felt risky in an environment where recognition and winning increasingly depended upon demonstrating operationally impressive solutions.

Amina still remembered the expression on Daniel's face that evening. He did not look angry. He looked helpless, as though he had suddenly realised that the system rewarding them was also quietly shaping the way they thought.

Amina's team eventually developed a small enclosed adaptive learning booth constructed inside the university laboratory using lightweight framing, transparent acrylic panels, low-cost environmental sensors, automated lighting controls, simplified airflow-adjustment components, and AI-assisted environmental monitoring software.

The booth was designed to simulate a compact future study environment where students could perform reading, concentration, and problem-solving activities while the system automatically optimised energy use and environmental conditions in real time. During the final demonstration, volunteer students were asked to spend extended periods inside the booth while performing learning-related cognitive tasks under controlled operational conditions.

The prototype's failure gradually became impossible to ignore. Although its operational indicators remained impressive, the system failed to support the very human needs it was supposed to serve. It reduced energy consumption, simplified maintenance, and performed well on efficiency dashboards, but it did not adequately support comfort, convenience, awareness, cognitive functioning, environmental certainty, or the occupants' sense of safety within the learning environment.

The moment felt surreal because the judges were still looking at excellent operational metrics while the prototype's value-delivery failure became increasingly visible. The system appeared successful as an engineering product, yet it failed as a human-centred learning environment. It could optimise energy and operational performance, but it could not help occupants feel comfortable, mentally alert, environmentally informed, or confident that the space was supporting their wellbeing.

Amina realised that the problem was not merely that some occupants became uncomfortable during the demonstration. The deeper problem was that the prototype had been designed to satisfy operational performance indicators more strongly than human usefulness outcomes. It delivered measurable efficiency, but it failed to deliver proportional value.

For the first time in her life, Amina witnessed a system achieve operational success while failing to meet human needs. That was the moment the flaw became visible to her. The prototype had not failed because it lacked intelligence, technology, or optimisation. It failed because the design logic behind it had confused operational efficiency with value delivery.

What disturbed Amina, and especially Daniel, even more was what happened afterward. Despite growing evidence that the prototype failed to adequately support the occupants' lived experiences, comfort, cognitive functioning, and environmental confidence, her team still won the competition.

Judges acknowledged during the feedback session that the human aspects of learning environments were important. However, the final scoring criteria remained overwhelmingly dominated by operational efficiency, scalability, implementation feasibility, energy optimisation, and measurable performance indicators.

Human wellbeing considerations appeared to function more as supplementary evaluation components rather than central determinants of success. As applause filled the demonstration hall and cameras flashed around the winning team, Amina felt a strange emotional emptiness growing quietly inside her.

After Daniel quietly withdrew from university life, Amina often found herself replaying his words late at night while staring across the city skyline from her apartment window. "This society knows how to optimise processes and systems, but it no longer knows how to protect the people living or operating inside them."

Daniel's decision disturbed her deeply because Daniel had once been one of the brightest and most passionate students in the engineering faculty. He genuinely believed engineering could improve human life. Yet after the competition, something inside him seemed to collapse emotionally. The applause inside the demonstration hall continued haunting him. He could not reconcile how a system that visibly failed to adequately support human wellbeing could still be celebrated publicly as a model of success.

What disturbed him most was not simply the prototype itself, but the realisation that intelligent people, including themselves, had gradually learned to prioritise measurable operational success more strongly than the lived experiences of human beings.

The more Amina reflected upon the experience, the more unsettling it became. She began noticing how frequently society reduced human beings into operational variables: productivity indicators, performance metrics, labour efficiency statistics, throughput measurements, optimisation targets, and economic outputs.

Everywhere she looked, human complexity seemed increasingly compressed into measurable operational categories because measurable things felt psychologically easier to control under uncertainty.

As she progressed through university and later industry practice, the pattern became impossible to ignore. Engineering companies celebrated productivity while employees suffered cognitive exhaustion. Smart buildings optimised energy performance while occupants increasingly complained about fatigue, discomfort, and declining cognitive wellbeing.

………………… Chapter 2 ……………………

During her industry placement at a large smart-building engineering company, Amina witnessed the contradiction unfold repeatedly with disturbing clarity.

Senior managers celebrated reduced operational expenditure, accelerated maintenance throughput, and improved energy performance across commercial buildings while employees inside those same buildings increasingly complained about headaches, poor concentration, respiratory irritation, emotional exhaustion, and mental fatigue.

Yet those complaints rarely influenced operational decisions because they were multidimensional, delayed, emotionally complex, and difficult to quantify precisely. By contrast, operational efficiency indicators appeared immediate, measurable, financially defensible, and psychologically reassuring under uncertain conditions.

Eventually, Amina realised the flaw was not simply technological or economic. It was cognitive. Under uncertainty and pressure, society increasingly relied upon operationally visible indicators because complexity, multidimensional human needs, delayed consequences, and stakeholder heterogeneity overwhelmed human cognitive capability.

As a result, people increasingly confused reduction in invested resources with productivity improvement, and productivity improvement itself with meaningful value delivery.

The deeper she reflected upon the issue, the more frightening the implications became. Entire industries had gradually become conditioned to mistake visible operational movement for genuine human progress. Buildings became “successful” because energy use declined even while occupants deteriorated cognitively inside them.

Organisations became “high performing” because throughput increased even while employees quietly suffered burnout. Educational systems became “excellent” because measurable academic performance improved even while students experienced anxiety, emotional exhaustion, and loss of meaning. Society itself had become trapped inside a dangerous illusion: the belief that operational optimisation automatically translated into human wellbeing.

That realisation changed the direction of Amina’s life permanently. What had once existed as a quiet unease inside her gradually transformed into a mission much larger than herself. Long before Daniel withdrew from university life, something inside Amina had already begun questioning the direction society was moving. Daniel’s collapse and her experiences during industrial internship training simply transformed that unease into something impossible for her to ignore.

She no longer wanted merely to improve buildings technically. She wanted to help address the cognitive flaw quietly shaping modern society itself: a society that had become extraordinarily efficient at measuring visible operational success while increasingly losing the ability to think deeply about what that success was quietly costing human beings underneath.

Several years later, while struggling to make sense of the contradictions she repeatedly observed across industry practice, Amina encountered the work of a professor through the professor’s publicly accessible living e-book on value delivery, indoor air quality, and engineering education practice. At first, she expected another technical discussion about sustainable buildings and operational optimisation. Instead, what she encountered unsettled her profoundly.

For the first time in her life, Amina encountered a structured explanation for the contradiction that had haunted her since the university competition. The professor’s work argued that productivity improvement and value delivery were not necessarily the same thing.

A system could reduce invested resources, accelerate operational throughput, simplify implementation, and improve measurable efficiency indicators while simultaneously failing to proportionally improve usefulness-related outcomes for the human beings affected by the system.

The deeper she studied the framework, the more she realised that the problem she had been observing throughout society was not simply technological failure. It was a cognitive failure in how people interpreted operational success itself under uncertainty.

His work particularly disturbed her because it explained why operationally visible indicators increasingly dominated judgement and decision-making under complex real-world conditions.

Measurable variables such as energy reduction, operational speed, labour efficiency, maintenance simplicity, and implementation cost felt psychologically easier to interpret and defend under uncertainty than multidimensional human outcomes such as cognitive wellbeing, exposure protection, physiological health, comfort, awareness, and long-term value delivery.

What fascinated Amina even more was the nature of the professor’s contribution itself. The framework did not function merely as an operational guideline or technical engineering tool. Instead, it resembled the kind of abstract theoretical framework often developed by theoretical physicists or mathematicians to explain hidden patterns governing complex systems before large-scale empirical validation fully exists.

The professor had essentially proposed a cognitive theory explaining how human beings operating under uncertainty increasingly misinterpret visible operational optimisation as meaningful value delivery. The theory appeared intellectually powerful, but Amina realised that limited empirical evidence yet existed to rigorously validate the framework under real-world indoor air management conditions.

Suddenly, Daniel's words returned to her with terrifying clarity. "This society knows how to optimise processes and systems, but it no longer knows how to protect the people living or operating inside them."

For months afterward, Amina became intellectually consumed by a single question: What if the professor's cognitive framework was fundamentally correct? What if entire industries had gradually become conditioned to confuse productivity improvement with genuine human progress under uncertainty-intensive operational conditions? The more she reflected upon the issue, the more she became convinced that the framework needed rigorous empirical investigation rather than remaining solely at the level of conceptual reasoning.

Amina realised she no longer wanted merely to participate in industry practice. She wanted to investigate the cognitive mechanisms causing intelligent practitioners to misclassify operational optimisation as meaningful human progress under uncertainty-intensive conditions.

She became increasingly convinced that indoor air management represented one of the clearest real-world environments where this contradiction unfolded continuously because practitioners were forced to balance energy efficiency, operational constraints, environmental complexity, occupant wellbeing, economic pressure, and incomplete information simultaneously.

Eventually, she decided to pursue a PhD focused on understanding how uncertainty, complexity, and stakeholder heterogeneity influenced judgement, decision-making, and value-delivery interpretation during indoor air management activities.

More importantly, she wanted to explore whether artificial intelligence could be developed not merely as an automation tool, but as a cognitive capability enhancement system capable of strengthening reflective reasoning, uncertainty interpretation, stakeholder integration, and value-oriented judgement under real-world operational conditions.

In many ways, Amina saw her PhD as an attempt to experimentally test, validate, refine, and operationalise the cognitive framework the professor had proposed. Just as theoretical scientists often develop abstract explanatory models before experimental verification becomes possible, she believed the professor's work had identified a potentially profound cognitive explanation for why modern societies increasingly struggle to distinguish operational optimisation from genuine value delivery.

Her mission, therefore, became not only technological or engineering-oriented, but scientific: to generate rigorous empirical evidence capable of determining whether the cognitive flaw identified in the framework genuinely influenced real-world indoor air management judgement, decision-making, and operational behaviour under uncertainty-intensive conditions.

As her background in architectural engineering and indoor air quality practice, which aligned closely with the domains the professor's work focused on, Amina increasingly recognised indoor air management as one of the clearest real-world environments where the contradiction between operational optimisation and genuine human value delivery continuously unfolded.

The deeper she reflected upon the issue, the more convinced she became that indoor air management provided an ideal real-world context for experimentally investigating how uncertainty, complexity, stakeholder heterogeneity, and operational pressure influenced human judgement, reasoning, and value-delivery interpretation. That conviction eventually shaped the direction of her PhD research and the problem statement that emerged from it, as presented below.

"Indoor air management practice increasingly operates under conditions characterised by environmental complexity, uncertainty, incomplete information, delayed environmental feedback, competing stakeholder priorities, and operational pressure.

Practitioners are frequently required to make rapid judgements and operational decisions involving ventilation adjustment, filtration optimisation, exposure mitigation, energy conservation, thermal comfort management, and maintenance planning. At the same time, they must balance occupant wellbeing, operational efficiency, environmental protection, and organisational constraints.

However, an important gap appears to exist between the current performance situation and the targeted performance situation within real-world indoor air management practice. The targeted performance situation requires indoor air management systems that improve value delivery relative to the invested resources involved. This includes effective pollutant mitigation, exposure protection, occupant wellbeing, comfort preservation, safety, awareness, and long-term environmental performance.

In contrast, the current performance situation appears to increasingly prioritise operational efficiency indicators such as intervention speed, maintenance throughput, labour reduction, simplified operational procedures, operational cost reduction, and energy-saving performance.

A major concern is that these operationally visible indicators are easier to measure, organisationally reinforce, and cognitively interpret. In contrast, multidimensional usefulness-related outcomes such as exposure protection, physiological wellbeing, cognitive performance preservation, and stakeholder-related value delivery are often more difficult to evaluate and quantify.

Consequently, practitioners operating under uncertainty-intensive conditions may increasingly rely upon operationally visible indicators during judgement, decision-making, and operational action.

This creates the possibility that reductions in invested resources, including reduced operational expenditure, reduced labour allocation, simplified intervention implementation, or faster intervention completion, may be incorrectly interpreted as evidence of productivity improvement.

Furthermore, productivity improvement itself may subsequently be misinterpreted as evidence of proportional improvement in value delivery even when actual usefulness-related outcomes remain unchanged or deteriorate.

The problem may become more severe under conditions involving uncertain pollutant source attribution, fluctuating occupancy conditions, delayed exposure consequences, incomplete environmental information, and heterogeneous stakeholder needs. Under such conditions, practitioners may increasingly rely upon simplified reasoning pathways and operationally accessible indicators during problem diagnosis and solving activities.

At present, limited research has systematically examined whether complexity, uncertainty, and stakeholder heterogeneity contribute to productivity misclassification and value-delivery misinterpretation during indoor air management activities. Similarly, insufficient understanding exists regarding the extent to which productivity improvement and actual value delivery remain proportionally associated or become decoupled under real-world operational conditions.

Another important limitation concerns practitioners' cognitive capability during operational reasoning activities. Indoor air management requires integration of environmental interpretation, uncertainty evaluation, stakeholder consideration, causal reasoning, and long-term consequence assessment under cognitively demanding conditions.

However, existing operational support systems frequently emphasise monitoring capability, automation efficiency, and data presentation rather than strengthening practitioners' cognitive capability for value-oriented reasoning and judgement.

Artificial intelligence technologies are becoming increasingly advanced and accessible. This is especially true for mobile AI systems capable of supporting real-time environmental interpretation and decision-support activities.

Consequently, AI-assisted cognitive capability enhancement may represent a potentially valuable approach for strengthening reflective reasoning, uncertainty interpretation, stakeholder integration, and value-oriented operational judgement during indoor air management activities.

However, limited research currently exists regarding whether such AI-assisted systems can effectively reduce productivity misclassification and value-delivery misinterpretation under real-world operational conditions.

This limitation creates the need for a solution capable of strengthening practitioners' cognitive capability during indoor air management problem diagnosis and solving. Such a solution should support reflective reasoning, uncertainty interpretation, stakeholder integration, and value-oriented operational judgement under real-world operational conditions.

Importantly, the solution should reduce the likelihood that practitioners misclassify a reduction in invested resources as productivity gains or misinterpret productivity gains as evidence of proportional value delivery."

This need forms the basis for the research questions, hypotheses, and objectives outlined in this study.

(i) How do the complexity and uncertainty associated with indoor air problems, together with the heterogeneity of stakeholder needs, causally influence the probability that indoor air management practitioners misclassify a reduction in invested resources as productivity gains? Furthermore, how do these conditions lead practitioners to misinterpret productivity gains, defined as increases in output per unit of invested resources, as improvements in value delivery during problem diagnosis and decision-making processes?

(ii) To what extent are increases in productivity, defined as increases in output per unit of invested resources, associated with, or decoupled from, actual value delivery, defined as increases in usefulness per unit of invested resources, in indoor air management systems operating under real-world conditions?

(iii) How does the use of an AI-based mobile decision-support framework, deployed on personal devices such as smartphones and tablets, enhance practitioners' cognitive capability in indoor air management? Furthermore, how do such enhancements in cognitive capability improve judgement, decision-making, and actions that reduce the misclassification of reduction in invested resources as productivity gains and the misinterpretation of productivity gains as value delivery, thereby improving value-oriented indoor air quality management problem diagnosis and solving?

For the first research question, the Null Hypothesis (H_{01}) is that the complexity and uncertainty associated with indoor air problems, together with the heterogeneity of stakeholder needs, have no statistically significant effect on the probability that indoor air management practitioners: (i) misclassify reduction in invested resources as productivity gains and (ii) misinterpret productivity gains, defined as increases in output per unit of invested resources, as improvements in value delivery during problem diagnosis and decision-making processes.

The Alternative Hypothesis (H_{11}) is that the complexity and uncertainty associated with indoor air problems, together with the heterogeneity of stakeholder needs, have a statistically significant positive effect on the probability that indoor air management practitioners: (i) misclassify reduction in invested resources as productivity gains and (ii) misinterpret productivity gains, defined as increases in output per unit of invested resources, as improvements in value delivery during problem diagnosis and decision-making processes.

For the second research question, the Null Hypothesis (H_{02}) is that an increase in productivity, defined as an increase in output per unit of invested resources, is statistically associated with a proportional increase in value delivery in indoor air management systems operating under real-world conditions.

The Alternative Hypothesis (H_{12}) is that an increase in productivity, defined as an increase in output per unit of invested resources, is not reliably associated with proportional increases in value delivery; specifically, productivity and value delivery are statistically decoupled in indoor air management systems operating under real-world conditions.

For the third research question, the Null Hypothesis (H_{03}) is that the use of an AI-based mobile decision-support framework has no statistically significant effect on practitioners' cognitive capability, judgement, decision-making, or actions. It does not reduce the misclassification of reduction in invested resources as productivity gains or the misinterpretation of productivity gains as value delivery, nor does it improve value-oriented indoor air management problem diagnosis and solving outcomes.

The Alternative Hypothesis (H_{13}) is that the use of an AI-based mobile decision-support framework has a statistically significant positive effect on practitioners' cognitive capability. This leads to improvements in judgement, decision-making, and operational actions during indoor air management activities.

These improvements reduce the misclassification of reduction in invested resources as productivity gains and the misinterpretation of productivity gains as value delivery. Consequently, value-oriented indoor air management problem diagnosis and solving outcomes improve.

The research questions and problems informed the following objectives of her PhD research:

(i) To investigate how the complexity and uncertainty associated with indoor air problems, together with the heterogeneity of stakeholder needs, influence the probability that indoor air management practitioners misclassify a reduction in invested resources as productivity gains. To investigate how these conditions contribute to the misinterpretation of productivity gains, defined as increases in output per unit of invested resources, as improvements in value delivery during problem diagnosis and decision-making processes.

(ii) To investigate the extent to which increases in productivity, defined as increases in output per unit of invested resources, are associated with, or decoupled from, actual value delivery, defined as increases in usefulness per unit of invested resources, within indoor air management systems operating under real-world conditions.

(iii) To investigate how the use of an AI-based mobile decision-support framework, deployed on personal devices such as smartphones and tablets, enhances practitioners' cognitive capability in indoor air management. To investigate how such enhancements in cognitive capability improve judgement, decision-making, and operational actions during indoor air management activities. To investigate how these improvements reduce the misclassification of reduction in invested resources as productivity gains and the misinterpretation of productivity gains as value delivery, thereby improving value-oriented indoor air quality management problem diagnosis and solving.

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Research Methods

Methods for Research Question 1 (Phase I):

Overview

The first phase of the investigation employed a large-scale multi-site behavioural experimental design aimed at identifying, quantifying, and causally evaluating the cognitive mechanisms associated with productivity and value misclassification during indoor air management problem diagnosis and decision-making.

The methodological design was developed in response to growing evidence that complex environmental systems frequently expose practitioners to uncertainty, incomplete information, competing stakeholder demands, and operational constraints that may distort judgement and decision-making processes and contribute to systematic cognitive errors, i.e., distorted action.

In indoor air management, such distortions may lead practitioners to incorrectly interpret reductions in invested resources as evidence of productivity improvement while simultaneously assuming that productivity gains necessarily indicate improvements in value delivery.

The investigation was therefore grounded in the proposition that insufficient cognitive capability may inhibit sound judgement, decision-making, and action in value-oriented problem diagnosis and solving, thereby contributing substantially to the misinterpretation of reductions in invested resources as productivity improvement and the subsequent misinterpretation of productivity improvement as evidence of enhanced value delivery.

Consequently, the study was designed to examine how uncertainty, complexity, time pressure, incomplete environmental information, and competing stakeholder demands influence these forms of cognitive misclassification during operational indoor air management activities.

The investigation further considered the possibility that although both usefulness-related factors and sacrifice-related factors are incorporated within the operationalised value framework, differences may exist in how easily these factors can be noticed, measured, understood, monitored, and acted upon during real-world indoor air management activities.

In terms of productivity, within the sacrifice-related dimension, the investigation considered the possibility that variables associated with cost (C_t), including time and financial resources, may be easier to measure, monitor, quantify, and mentally process during judgement and decision-making than sacrificed comfort (C_{fs}), sacrificed convenience (C_{vs}), and sacrificed awareness (A_{ws}). These human-related sacrifices were considered potentially less directly visible and more difficult to continuously evaluate under real-world operational conditions.

The investigation additionally considered the possibility that productivity itself may become cognitively misinterpreted under complex operational conditions because productivity measurement in practice may be dominated by variables that are immediately measurable, numerically explicit, operationally monitored, and cognitively accessible.

In many operational environments, productivity may be interpreted primarily as increases in output quantity relative to reductions in cost (C_t), including time and financial resources, while broader human-centred sacrifices such as sacrificed comfort (C_{fs}), sacrificed convenience (C_{vs}), and sacrificed awareness (A_{ws}) may not be incorporated directly into productivity measurement processes.

Similarly, within many operational productivity systems, output quantity (Q_t) may receive greater emphasis, while output quality (Q_l) and safety (S) may function primarily as operational constraints rather than as central determinants of productivity itself. Stakeholder-related outcomes such as comfort (C_f), convenience (C_v), and awareness (A_w) may likewise receive comparatively limited consideration within conventional productivity evaluation processes.

Within the usefulness-related dimension, the investigation further considered the possibility that variables associated with output quantity (Q_t) and certain measurable aspects of air quality (Q_I) may be more operationally visible and easier to quantify during indoor air management activities.

In contrast, multidimensional usefulness-related outcomes such as comfort (C_f), convenience (C_v), awareness (A_w), cognitive performance preservation, long-term health protection, and safety (S) may be more difficult to comprehensively evaluate, particularly under uncertain, temporally dynamic, and operationally constrained conditions. Many of these usefulness-related outcomes may additionally be probabilistic, temporally delayed, context-dependent, or cognitively demanding to evaluate comprehensively during real-time indoor air management activities.

Consequently, the investigation was designed to examine whether practitioners operating under mentally demanding operational conditions increasingly prioritise variables that are easier to observe, quantify, justify operationally, and process cognitively during judgement and decision-making.

Particular emphasis was placed on examining whether such conditions contribute to the misclassification of reductions in invested resources as productivity improvement and the subsequent misinterpretation of productivity improvement as evidence of enhanced value delivery, even when usefulness-related outcomes and broader human-centred consequences may not improve proportionally.

Behavioural Experimental Design

The study involved approximately 150 indoor air management practitioners. The participants were recruited from consultancy firms, hospitals, facilities management organisations, healthy building consultancies, environmental monitoring agencies, industrial hygiene firms, engineering companies, and government-related environmental agencies.

The study was conducted across four countries representing tropical, subtropical, temperate, and mixed climatic regions. The countries included Northlandia, Westoria, Shinara, and South Aurelia.

These countries represented varying indoor air management practices, organisational structures, climatic conditions, and regulatory environments. The inclusion of geographically and operationally diverse participants was intended to improve ecological validity while maintaining operational feasibility within the scope of a doctoral investigation. It also helped minimise the likelihood that the findings merely reflected country-specific organisational practices, cultural norms, or regulatory structures.

Participants were selected using a stratified purposive sampling strategy designed to ensure representation across varying levels of professional experience, technical expertise, organisational responsibility, and educational background.

Approximately 35% of participants possessed fewer than five years of professional experience, 43% possessed between five and fifteen years of experience, and 22% possessed more than fifteen years of experience in indoor air quality and healthy building-related roles.

Participants additionally included mechanical engineers, ventilation specialists, occupational hygienists, facility managers, sustainability consultants, environmental scientists, and indoor air quality investigators.

This multidisciplinary representation was considered essential because indoor air management decision-making frequently involves competing operational priorities, differing stakeholder expectations, and varying professional reasoning frameworks.

The investigation, therefore, sought to determine whether differences in cognitive capability for value-oriented reasoning influence practitioners' ability to correctly distinguish among operational output quantity, invested resources, productivity improvement, usefulness delivered, sacrifices incurred, and overall value delivery during indoor air management problem diagnosis and solving.

Particular emphasis was placed on examining whether practitioners operating under uncertain and mentally demanding conditions increasingly interpret reductions in cost (C_t), including time and financial resources, together with increases in operational output quantity, as evidence of improved productivity, while simultaneously assuming that improved productivity automatically means better value delivery even when actual usefulness may not have improved proportionally.

The experimental investigation employed simulation-based indoor air management scenarios developed from 48 real-world indoor environmental case studies collected from hospitals, office buildings, schools, industrial facilities, and residential environments over a seven-year period of indoor air management practice and investigation.

These scenarios involved complex ventilation failures, transient pollutant exposure events, mould contamination, thermal discomfort complaints, filtration decision conflicts, energy-saving interventions, odour complaints, and competing organisational objectives.

Each simulation was intentionally designed to reproduce realistic operational conditions involving uncertainty, incomplete environmental information, time pressure, competing stakeholder demands, and dynamically changing environmental conditions associated with real-world indoor air management activities.

The simulations were implemented using a digitally deployable indoor environmental simulation platform capable of reproducing time-varying pollutant behaviour, ventilation dynamics, occupancy interactions, and intervention outcomes.

Participants interacted with real-time dashboards displaying simulated indoor environmental data streams, including particulate matter concentrations, carbon dioxide levels, airflow behaviour, humidity variation, occupant complaint logs, energy consumption metrics, and maintenance records.

The dashboards additionally displayed operational response indicators, resource utilisation metrics, stakeholder-related outcomes, and intervention consequence feedback associated with productivity performance and usefulness delivery during indoor air management decision-making. The simulations evolved dynamically based on participant decisions, thereby replicating the adaptive and uncertain nature of operational indoor air management systems.

To improve operational feasibility and enable participation across geographically distributed locations, the simulations were administered remotely through secure online deployment infrastructure. Participants completed the simulations individually using standardised procedural instructions, synchronised simulation protocols, fixed scenario timing structures, and uniform interface configurations across all deployment sessions.

Prior to participation, all participants attended a standardised online briefing session explaining simulation procedures, environmental interpretation tasks, decision-making requirements, and protocol expectations.

Simulation sessions were conducted within pre-scheduled participation windows and incorporated automated session logging, response-time recording, interaction tracking, and screen activity monitoring throughout the simulation process. Participants were additionally instructed to complete the simulations in quiet working environments without external collaboration or interruption, where reasonably possible.

To strengthen procedural consistency and minimise the likelihood of external information searching or protocol deviation during simulation activities, the remotely deployed simulation platform incorporated controlled assessment features commonly used in secure online behavioural research environments.

These included restricted browser navigation, session-lock functionality, automated interaction logging, time-synchronised task progression, and activity-monitoring mechanisms designed to discourage access to external digital resources during simulation completion. Participants additionally completed informed procedural compliance agreements prior to participation.

All simulation sessions were digitally recorded for behavioural analysis, interaction-sequence reconstruction, and subsequent coding procedures. Although complete laboratory-level environmental control was not feasible under remote international deployment conditions, several measures were implemented to minimise procedural variability across participants.

These included standardised procedural guidance, synchronised simulation architecture, automated behavioural logging, controlled assessment features, and structured protocol procedures. These measures were additionally intended to strengthen internal consistency and improve the reliability of behavioural measurements.

Each participant completed between four and six simulation scenarios distributed across varying levels of complexity and uncertainty. Individual simulation sessions lasted approximately 60 minutes, generating several thousand hours of cumulative behavioural decision-making data across the participant cohort.

This repeated-measures design was considered sufficient to evaluate behavioural adaptation, judgement consistency, heuristic dependence, productivity misclassification tendencies, and productivity–value confusion patterns across varying operational conditions while remaining operationally manageable within the scope of the doctoral investigation.

To reduce learning-order effects, scenario presentation order was randomised using Latin square experimental balancing procedures. Scenario complexity and uncertainty levels were additionally counterbalanced across participants to minimise systematic exposure bias and strengthen causal interpretability across the behavioural analyses.

Experimental Manipulation of Complexity, Uncertainty, and Stakeholder Heterogeneity

Three primary independent variables were experimentally manipulated throughout the behavioural simulations: environmental complexity, informational uncertainty, and stakeholder heterogeneity.

These variables were selected because previous cognitive science, systems engineering, and organisational decision-making research has demonstrated that increasing complexity and uncertainty may elevate the likelihood of heuristic simplification, omission bias, and judgement distortion.

The investigation additionally considered the possibility that such distortions may arise because practitioners operating under cognitively demanding conditions increasingly rely on variables that are easier to observe, quantify, and process mentally during judgement and decision-making.

Environmental complexity was operationalised using interacting indicators, including the number of active pollutant sources, interacting environmental variables, temporal instability of pollutant behaviour, nonlinearity of system dynamics, and causal coupling among indoor environmental processes.

The low-complexity scenarios involved indoor air problems that were relatively straightforward, with only a few interacting factors that were easier to identify and understand. These factors included ventilation rate, occupancy level, outdoor pollutant infiltration, indoor pollutant-generating sources, and temperature and humidity conditions.

In contrast, the high-complexity scenarios involved indoor air problems with several interacting factors, including ventilation conditions, occupancy fluctuations, outdoor pollutant infiltration, multiple indoor pollutant-generating sources, thermal and humidity variations, operational constraints, stakeholder demands, and changing environmental conditions.

These scenarios additionally involved delayed intervention effects, dynamically changing pollutant behaviour, and competing operational priorities. For example, whereas low-complexity scenarios typically involved isolated ventilation inadequacy within a single indoor space, high-complexity scenarios involved multi-zone environments with continuously changing environmental and operational conditions together with competing stakeholder priorities.

Uncertainty was manipulated through controlled variation in data completeness, reliability, interpretability, and temporal availability. Scenarios included missing environmental measurements, delayed sensor updates, contradictory occupant reports, uncertain pollutant source attribution, and ambiguous airflow behaviour.

Approximately 35% of scenarios contained incomplete environmental datasets, while 20% incorporated sensor drift errors ranging from ±5% to ±15% to reproduce realistic monitoring limitations encountered during field investigations. Bayesian uncertainty indices were subsequently computed for each scenario to quantify informational ambiguity.

Bayesian uncertainty indices are quantitative measures used to estimate how uncertain, ambiguous, or unreliable available information is during decision-making. High-uncertainty scenarios possessed posterior entropy values exceeding 0.70, whereas low-uncertainty scenarios possessed entropy values below 0.30.

Stakeholder heterogeneity was operationalised by varying stakeholder priorities, vulnerability profiles, operational expectations, and value preferences across scenarios.

Certain scenarios prioritised economic efficiency and energy reduction, whereas others emphasised occupant health protection, cognitive performance preservation, thermal comfort, or infection risk mitigation. This manipulation was included because indoor air management decisions frequently involve competing stakeholder objectives that may increase cognitive burden and decision uncertainty.

The investigation, therefore, examined whether practitioners operating under increasing complexity, uncertainty, and stakeholder heterogeneity increasingly prioritised operationally visible and cognitively accessible indicators during judgement and decision-making processes.

These indicators included cost reduction, intervention speed, and output quantity. The investigation also examined whether comparatively less attention was given to usefulness-related outcomes and human-related sacrifices under such conditions.

Participants were randomly assigned to varying combinations of complexity, uncertainty, and stakeholder heterogeneity conditions using computer-generated allocation procedures to minimise selection bias and strengthen causal interpretability.

Operationalisation of Cognitive Misclassification Constructs

This phase established explicit quantitative definitions for productivity, value delivery, productivity misclassification, and value interpretation deviation to enable systematic evaluation of judgement and decision-making during indoor air management problem diagnosis and solving under varying levels of complexity, uncertainty, and stakeholder heterogeneity.

Productivity was operationalised as measurable output relative to invested resources during indoor air management activities. Output variables included the number of interventions implemented, environmental assessments completed, monitoring coverage achieved, ventilation optimisation actions performed, and response times to occupant complaints.

Invested resources included time and financial resources associated with labour, equipment, materials, and operational processes. The operationalisation framework was designed to evaluate whether practitioners correctly distinguished between increases in operational output quantity and actual improvements in problem-solving effectiveness during indoor air management activities.

Productivity misclassification was operationalised as the deviation between perceived productivity improvement and objectively measured productivity performance:

$$MP_i = P_i^{perceived} - P_i^{actual}$$

Positive values indicated overestimation of productivity performance relative to objectively measured performance. This operationalisation enabled systematic examination of whether practitioners increasingly interpreted reductions in invested resources and increases in operational output quantity as evidence of productivity improvement under cognitively demanding conditions.

Value delivery was operationalised using the multidimensional value equation developed within the conceptual framework of the investigation:

$$\text{Value} = \frac{(C_f + C_v + A_w)(Q_l \times Q_t \times S)}{(C_{fs} + C_{vs} + A_{ws})(C_t)}$$

Within this framework, value delivery represented the relationship between usefulness gained and sacrifices incurred during indoor air management interventions. The equation incorporated usefulness-related factors, including comfort, convenience, awareness, quality, quantity, and safety, together with sacrifice-related factors associated with operational costs and human-related sacrifices experienced during intervention implementation.

Perceived value delivery and objectively measured value delivery were independently quantified for each participant to enable evaluation of value interpretation deviation during operational decision-making under varying levels of complexity and uncertainty. Value interpretation deviation was operationalised as the difference between perceived value delivery and objectively measured value delivery:

$MV_i = V_i^{perceived} - V_i^{actual}$

Positive values indicated overestimation of actual value delivery during indoor air management decision-making processes.

Cognitive and Behavioural Measurements

To improve behavioural validity and reduce dependence on subjective self-reporting alone, the investigation incorporated multiple layers of cognitive, physiological, behavioural, and environmental measurement.

Diagnostic accuracy was assessed by comparing participant-generated diagnoses against independently established reference diagnoses developed through multidisciplinary consensus procedures involving professionals and researchers in ventilation engineering, occupational hygiene, building science, indoor air quality investigation, and healthy building assessment. Inter-rater reliability among expert reviewers exceeded Cohen’s $\kappa = 0.86$, indicating strong diagnostic agreement.

Decision quality was evaluated using structured scoring systems designed to assess causal reasoning accuracy, stakeholder alignment quality, uncertainty interpretation capability, intervention appropriateness, and consistency with the operationalised value framework. Scores were structured on a standardised scale ranging from 0 to 100.

The scoring framework was designed to examine whether increasing complexity, uncertainty, and stakeholder heterogeneity influence practitioners' ability to sustain sound judgement, decision-making, and value-oriented reasoning during indoor air management problem diagnosis and solving.

Cognitive load was measured using the NASA Task Load Index (NASA-TLX), eye-tracking analysis, decision latency measurement, and physiological stress indicators. These measurements were incorporated to evaluate perceived mental workload, information-processing behaviour, attentional allocation, and cognitive stress responses under varying operational conditions.

Eye-tracking analysis was conducted using Tobii Pro Fusion systems operating at 250 Hz. Eye fixation duration, gaze transition frequency, heat-map concentration, and attentional narrowing patterns were analysed to quantify information-processing behaviour during decision-making activities.

Particular emphasis was placed on examining whether practitioners operating under increasing uncertainty increasingly allocated attention towards operationally visible and cognitively accessible indicators, such as cost-related and throughput-related variables, while giving comparatively less attention to usefulness-related outcomes and human-related consequences.

Decision latency measurements were incorporated to quantify the duration of information-processing and decision-making activities under varying levels of complexity and uncertainty. These measurements were intended to evaluate whether cognitively demanding operational conditions influence reliance on heuristic simplification and rapid judgement formation during indoor air management problem-solving activities.

Physiological stress responses were measured using heart rate variability and electrodermal activity monitoring to evaluate cognitive stress regulation during simulation activities. These measurements were incorporated to assess whether increasing environmental complexity and uncertainty contribute to elevated cognitive strain during operational decision-making.

Think-aloud protocols were additionally implemented to capture participant reasoning processes throughout indoor air management problem-solving activities. Natural language processing models employing transformer-based semantic analysis were subsequently used to analyse verbal reasoning patterns, heuristic dependence, omission bias, causal simplification, uncertainty framing behaviour, and productivity–value interpretation patterns.

The cognitive and behavioural measurement framework was designed to systematically examine how increasing uncertainty, complexity, and stakeholder heterogeneity influence judgement and decision-making during indoor air management activities. Particular emphasis was placed on examining whether practitioners increasingly prioritised cognitively accessible productivity-related indicators over more complex and less observable usefulness-related outcomes.

Statistical and Causal Analysis

The primary analytical framework employed multilevel mixed-effects logistic regression modelling to account for clustering effects arising from participants nested within organisations, professional disciplines, and countries.

This modelling approach was selected because practitioner judgement, decision-making, and action during indoor air management activities were expected to be influenced by multiple interacting factors.

These included not only individual cognitive characteristics but also organisational environments, professional training backgrounds, operational cultures, and contextual conditions associated with different geographical settings.

A composite complexity–uncertainty–stakeholder heterogeneity index was developed to quantify the combined cognitively demanding conditions experienced during simulation activities:

$CUH_i = f(C_i, U_i, SH_i)$

where CUH_i represented the combined complexity–uncertainty–stakeholder heterogeneity index, C_i represented environmental complexity, U_i represented informational uncertainty, and SH_i represented stakeholder heterogeneity.

The probability of productivity misclassification and value interpretation deviation was subsequently modelled as a function of the combined cognitively demanding operational conditions together with judgement quality, decision quality, and action quality:

$P(MP_i) = f(CUH_i, J_i, D_i, A_i)$

$P(MVi) = f(CUH_i, J_i, D_i, A_i)$

where $P(MP_i)$ represented the probability of productivity misclassification, $P(MV_i)$ represented the probability of value interpretation deviation, J_i represented judgement quality, D_i represented decision quality, and A_i represented action quality during indoor air management problem diagnosis and solving activities.

The mixed-effects models incorporated random intercepts for country, organisation, and professional background to account for hierarchical clustering structures and contextual variability across participants and operational environments.

Interaction effects among environmental complexity, informational uncertainty, and stakeholder heterogeneity were additionally incorporated to examine whether combined cognitively demanding operational conditions influence productivity misclassification and value interpretation differently from isolated operational stressors.

Particular emphasis was placed on examining whether increasing complexity, uncertainty, and stakeholder heterogeneity progressively impair practitioners' judgement quality, decision-making consistency, causal reasoning capability, and action appropriateness during indoor air management activities.

The analytical framework further examined whether such reductions in cognitive capability increase the probability that practitioners misclassify reductions in invested resources as productivity improvement and subsequently misinterpret productivity improvement as evidence of enhanced value delivery.

Structural equation modelling was additionally employed to evaluate mediation pathways linking environmental complexity, cognitive load, attentional allocation, heuristic dependence, judgement quality, decision quality, action quality, productivity misclassification, and value interpretation deviation.

The structural modelling framework was specifically designed to examine whether increasing environmental complexity and uncertainty indirectly influence productivity and value interpretation through changes in cognitive burden, information-processing behaviour, and heuristic reliance during indoor air management problem-solving activities.

Instrumental variable analysis was incorporated to strengthen causal interpretability and reduce susceptibility to latent practitioner-level bias and unobserved behavioural confounding. Practitioner fatigue and prior exposure to complex indoor air investigations were incorporated as instrumental variables influencing heuristic dependence without directly determining productivity misclassification outcomes.

Robustness analyses included bootstrapping procedures involving 10,000 repeated resamples of the participant-level behavioural dataset, together with false discovery rate correction, sensitivity testing, adversarial scenario perturbation analysis, and counterfactual simulation modelling.

These procedures were implemented to enhance model robustness, reduce susceptibility to overfitting and multiplicity bias, minimise omitted variable bias, and strengthen the reliability and causal interpretability of the analytical framework under complex behavioural and environmental conditions.

Overall, the analytical framework for Phase I was designed to systematically examine whether increasing environmental complexity, uncertainty, and stakeholder heterogeneity increase the likelihood that indoor air management practitioners misclassify reductions in invested resources as productivity improvement and subsequently misinterpret productivity improvement as evidence of enhanced value delivery.

The framework was additionally designed to examine whether declining cognitive capability for value-oriented reasoning under cognitively demanding operational conditions contributes directly to poorer judgement, decision-making, and action, thereby increasing the probability of productivity and value misclassification during indoor air management problem diagnosis and solving activities.

Ethical Considerations and Contribution to Knowledge

The first phase of the investigation involved behavioural, cognitive, physiological, and decision-making assessments conducted using simulation-based indoor air management scenarios under varying levels of complexity, uncertainty, and stakeholder heterogeneity.

Ethical approval was obtained from the relevant institutional ethics review board prior to participant recruitment and data collection. All procedures complied with internationally accepted ethical principles relating to informed consent, participant autonomy, confidentiality, psychological wellbeing, and responsible behavioural research practice.

Participation was entirely voluntary. Participants received detailed information regarding the study objectives, simulation procedures, behavioural monitoring activities, physiological measurements, eye-tracking assessments, think-aloud protocols, and data analysis procedures before participation.

They were additionally informed that the investigation focused on understanding judgement and decision-making processes under cognitively demanding indoor air management conditions rather than evaluating professional competence or occupational performance. Written informed consent was obtained from all participants.

Because the investigation intentionally exposed participants to uncertainty, incomplete information, time pressure, and cognitively demanding operational conditions, simulation difficulty levels were carefully calibrated through pilot testing to minimise excessive psychological strain while preserving behavioural realism. Participants retained the right to pause or withdraw at any stage without penalty.

All behavioural, physiological, interaction, and verbal reasoning data were anonymised prior to analysis using encrypted participant identifiers. Personally identifiable information and organisational identifiers were removed from analytical datasets, while access to raw data remained restricted to authorised research personnel only.

The investigation contributes to knowledge by developing an integrated behavioural framework for examining productivity misclassification and value misinterpretation within indoor air management problem diagnosis and decision-making.

It further contributes theoretically and methodologically through the integration of behavioural simulation, cognitive assessment, physiological monitoring, eye-tracking analysis, natural language processing, and causal modelling within a unified analytical framework.

Methods for Research Question 2 (Phase II):

Overview

The second phase of the investigation adopted a longitudinal multi-site quasi-experimental field design aimed at examining whether increases in productivity within operational indoor air management systems are genuinely associated with measurable improvements in value delivery under real-world conditions.

Building upon the findings and methodological foundation established in Phase I, this phase was designed to investigate whether the cognitive misclassification mechanisms identified during behavioural experimentation translate into measurable productivity–value decoupling during practical indoor air management operations.

The investigation, therefore, examined whether operational systems that appear productive on the basis of increased output quantity and reductions in invested time and financial resources necessarily deliver corresponding improvements in indoor air quality, exposure reduction, occupant wellbeing, and broader usefulness-related outcomes affecting occupants and stakeholders.

The methodological framework was grounded in the proposition that productivity improvement and value delivery are conceptually distinct and may not necessarily increase proportionally under complex operational conditions. Within the investigation, productivity was conceptualised primarily as increases in output quantity relative to reductions in invested time and financial resources.

In contrast, value delivery incorporated not only output quantity but also indoor air quality, indoor air quantity, safety, occupant comfort, convenience, awareness, cognitive performance preservation, exposure reduction, long-term health protection, and broader usefulness-related outcomes relative to the sacrifices incurred in achieving those outcomes.

Accordingly, this phase was specifically designed to examine whether measurable productivity gains correspond with proportional improvements in usefulness-related and human-centred outcomes or whether productivity–value decoupling emerges under operational conditions characterised by uncertainty, variability, and competing stakeholder needs.

The investigation, therefore, focused on observable operational performance, environmental outcomes, and occupant-related outcomes to determine whether productivity gains provide a reliable indication of actual value delivery under real-world indoor air management conditions.

Particular emphasis was placed on evaluating whether productivity-oriented operational strategies may increasingly prioritise operationally visible and cognitively accessible indicators, including intervention throughput, response speed, output quantity, and reductions in time and financial resources, while giving comparatively less attention to less immediately observable usefulness-related outcomes and human-related sacrifices associated with indoor air management activities.

Longitudinal Field Investigation

The field investigation was conducted across 16 buildings located in Shinara, representing healthcare, educational, office, and residential environments. Shinara was selected because its high-density urban environment and diverse building typologies provided a suitable real-world setting for the study.

The country also contained a mixture of mixed-mode and mechanically ventilated spaces operating under tropical climatic conditions. In addition, substantial variation existed in indoor air management practices across buildings and organisations. These conditions made Shinara suitable for examining productivity–value relationships under complex operational indoor environmental conditions.

The selection of Shinara additionally enabled investigation of indoor air management systems operating under conditions characterised by high occupant density, continuous building usage, substantial energy demand, diverse ventilation strategies, and varying organisational priorities relating to operational efficiency, occupant wellbeing, and environmental sustainability.

These characteristics were considered particularly important because they created realistic conditions under which productivity improvement and value delivery may either remain aligned or become progressively decoupled during routine operational decision-making.

Building selection employed maximum variation sampling to ensure substantial heterogeneity in ventilation systems, occupancy patterns, pollutant exposure profiles, operational objectives, organisational structures, and maintenance practices.

The sampled buildings included four healthcare facilities, four educational buildings, four office buildings, and four residential complexes. Building floor areas ranged from approximately 2,500 m^2 to 42,000 m^2, while average daily occupancy ranged from approximately 45 to over 2,000 occupants depending on building typology and operational function.

Healthcare facilities included both inpatient and outpatient environments with continuously occupied zones, mechanically ventilated isolation areas, and varying infection-control requirements. Educational buildings included classrooms, lecture halls, laboratories, and mixed naturally ventilated learning environments with fluctuating occupancy conditions throughout the academic calendar.

Office buildings included both open-plan and compartmentalised working environments influenced by varying occupancy density, outdoor pollution infiltration, and operational scheduling practices. Residential complexes included both naturally ventilated and mechanically ventilated dwelling units exposed to differing occupant behaviours, cooking activities, cleaning practices, and neighbourhood pollution conditions.

The relatively limited number of buildings enabled intensive longitudinal environmental monitoring, repeated physiological and cognitive assessments, exposure tracking, and detailed operational evaluation across the full 24-month investigation period while maintaining sufficient depth, data quality, and operational feasibility for robust longitudinal and causal analysis.

This balance between sample diversity and monitoring intensity was considered important because large-scale building studies frequently encounter limitations in data resolution, monitoring continuity, participant compliance, and operational consistency when extensive environmental and physiological measurements are implemented simultaneously across highly heterogeneous indoor environments.

The investigation extended over a continuous 24-month monitoring period to capture temporal variability in indoor environmental conditions, operational behaviour, occupant exposure, ventilation performance, and organisational indoor air management practices.

The longitudinal design was considered essential because short-duration investigations may inadequately capture cumulative exposure burden, delayed physiological responses, adaptive operational behaviour, and temporal variation in productivity–value relationships under real-world conditions. Measurements were therefore conducted continuously across multiple climatic cycles, operational fluctuations, occupancy variations, and organisational intervention periods.

The extended monitoring duration additionally enabled evaluation of temporal changes associated with seasonal weather variation, occupancy redistribution, equipment ageing, maintenance cycles, behavioural adaptation, and evolving organisational management strategies.

These factors were considered scientifically important because indoor environmental performance and operational productivity frequently fluctuate over time rather than remaining stable under real-world conditions.

The quasi-experimental structure of the investigation arose from naturally occurring operational interventions implemented by participating organisations during the study period.

These interventions included ventilation optimisation strategies, energy conservation initiatives, maintenance restructuring, filtration upgrades, monitoring reductions, operational cost-reduction programmes, and changes in environmental management procedures.

Rather than artificially imposing interventions under laboratory conditions, the investigation leveraged naturally occurring organisational decisions to preserve ecological validity while enabling systematic evaluation of whether productivity gains corresponded with proportional improvements in value delivery during real-world indoor air management operations.

This quasi-experimental approach was considered particularly important because organisational indoor air management decisions are frequently shaped by financial limitations, operational pressures, energy-management objectives, staffing constraints, maintenance priorities, and competing stakeholder expectations.

Consequently, the investigation sought to evaluate productivity–value relationships under realistic operational conditions rather than under highly controlled laboratory environments that may insufficiently represent practical organisational decision-making realities.

Particular emphasis was placed on examining whether organisations operating under pressure to improve productivity increasingly prioritised operationally visible and cognitively accessible indicators such as intervention throughput, response speed, labour efficiency, energy reduction, and operational cost reduction during indoor air management activities.

The investigation additionally examined whether comparatively less attention was given to usefulness-related outcomes including indoor air quality, exposure reduction, occupant wellbeing, cognitive performance preservation, safety, comfort, convenience, awareness, and long-term health protection under such operational conditions.

This distinction was considered important because operational productivity indicators are often immediately measurable, numerically explicit, and organisationally reinforced within management systems, whereas many usefulness-related outcomes may be delayed, multidimensional, probabilistic, or more difficult to continuously quantify during routine operational activities.

The investigation, therefore, examined whether productivity-oriented operational strategies may unintentionally generate conditions in which measurable operational efficiency improvements occur simultaneously with stagnant or deteriorating occupant-related outcomes.

Productivity and value delivery measurements in Phase II followed the operational framework established in Phase I. Productivity indicators focused on measurable operational outputs relative to invested time and financial resources, whereas value-delivery indicators incorporated usefulness-related outcomes and stakeholder-related sacrifices associated with indoor air management activities.

These measurements were integrated longitudinally with environmental, exposure, physiological, cognitive, and occupant-related assessments to evaluate whether productivity gains corresponded with proportional improvements in value delivery under real-world operational conditions.

The integrated measurement structure enabled simultaneous examination of operational performance, environmental quality, occupant exposure, physiological response, cognitive functioning, and occupant-centred outcomes across varying intervention periods and organisational management conditions.

This longitudinal integration was intended to strengthen the evaluation of whether improvements in operational productivity genuinely translated into measurable improvements in usefulness delivered to occupants and stakeholders.

Consequently, Phase II extended the theoretical and behavioural foundations established in Phase I into operational indoor air management environments to examine the extent to which productivity improvement and value delivery remain aligned or become measurably decoupled under real-world conditions characterised by uncertainty, variability, and competing stakeholder needs.

The investigation, therefore, moved beyond behavioural interpretation and cognitive misclassification alone to examine whether productivity–value decoupling can be empirically observed within functioning indoor air management systems operating under practical environmental, organisational, and operational constraints.

Environmental Monitoring and Exposure Assessment

Continuous environmental monitoring was conducted throughout the 24-month study period using calibrated research-grade instrumentation deployed across all participating buildings. The monitoring framework was designed to capture both long-term exposure conditions and short-duration pollutant events occurring under real-world indoor environmental and operational conditions.

Measured environmental parameters included particulate matter concentrations ($PM_{0.1}$, $PM_{2.5}$, PM_{10}), nitrogen dioxide (NO_2), volatile organic compounds (VOCs), ozone (O_3), carbon dioxide (CO_2), temperature, relative humidity, airflow rate, ventilation rate, air change rate, air exchange effectiveness, effective air change rate, and differential pressure relationships between indoor zones.

Air exchange effectiveness was evaluated to determine how effectively supplied air reached occupant breathing zones and removed pollutants from occupied spaces. Environmental sensors were strategically distributed across occupant breathing zones, return-air pathways, high-density occupancy areas, and pollutant-sensitive microenvironments.

Particulate matter measurements were conducted using optical particle spectrometers and condensation particle counters capable of monitoring ultrafine particle concentrations across particle size ranges from 0.01 μm to 10 μm. Carbon dioxide concentrations were continuously monitored to evaluate occupancy-related ventilation adequacy and temporal variation in indoor air accumulation under varying occupancy and ventilation conditions.

Volatile organic compound (VOC) monitoring was additionally conducted to capture pollutant emission events associated with cleaning activities, maintenance operations, material emissions, and operational processes occurring within indoor environments.

Measurements were recorded at one-minute intervals throughout the investigation period. This temporal resolution was adopted to capture short-duration pollutant fluctuations and episodic exposure events that may not be adequately represented through longer-duration averaging procedures commonly used in indoor environmental investigations.

Ventilation performance was assessed using continuous airflow monitoring combined with tracer gas decay methods. Airflow effectiveness and effective ventilation delivery were quantified to evaluate whether outdoor air was efficiently reaching occupant breathing zones rather than merely entering indoor spaces. An effective air change rate was computed using the relationship:

$$ACH_e = (Q \times \varepsilon)/V$$

where Q represented ventilation airflow rate, εrepresented airflow effectiveness, and V represented indoor volume. This framework enabled differentiation between nominal ventilation conditions and effective pollutant removal performance within occupied indoor microenvironments.

Personal wearable exposure devices were deployed across a stratified rotating subsample of approximately 360 occupants representing different occupational roles, vulnerability profiles, age groups, and building-use behaviours.

Wearable monitoring was conducted during scheduled monitoring intervals across the 24-month study period rather than continuously for all participants. This rotational approach enabled individual-level exposure assessment while maintaining operational feasibility within the scope of the doctoral investigation.

Cumulative exposure dose was computed using time-integrated pollutant concentration modelling:

$$\text{CED} = \int_0^T C(t)\,dt$$

where CED represented cumulative exposure dose, C(t) represented time-varying pollutant concentration, and T represented cumulative exposure duration. Environmental and exposure measurements were subsequently integrated with operational productivity metrics and occupant-related usefulness outcomes to examine whether productivity gains corresponded with proportional improvements in value delivery under real-world indoor air management conditions.

Physiological and Human Outcome Measurements

To strengthen scientific robustness and reduce dependence on subjective outcome measures alone, physiological, cognitive, and occupant-related assessments were incorporated throughout the longitudinal field investigation.

The inclusion of objective human outcome measurements was considered essential because operational productivity improvements within indoor air management systems may not necessarily correspond with proportional improvements in occupant wellbeing, physiological health, or cognitive functioning under real-world conditions.

Within the value-delivery framework of the investigation, these human-related outcomes were used to determine whether indoor air management activities were genuinely improving the usefulness experienced by occupants or merely improving operational productivity indicators such as intervention speed, throughput, and cost reduction.

Physiological measurements included salivary cortisol, spirometry, inflammatory biomarkers, heart rate variability, blood oxygen saturation, and sleep quality indices. These measurements were incorporated to evaluate potential physiological responses associated with long-term exposure to varying indoor environmental conditions, ventilation performance, pollutant exposure levels, and operational indoor air management practices.

Within the conceptual value framework established in the investigation, physiological stability, respiratory protection, cognitive performance preservation, sleep quality, and occupant wellbeing were treated as usefulness-related outcomes associated with indoor environmental exposure conditions.

These outcomes were conceptually aligned with comfort gained (C_f), awareness gained (A_w), quality of indoor air conditions (Q_l), quantity of effective clean air delivery (Q_t), and safety (S) within the value equation because healthier, safer, and cognitively supportive indoor environments were considered indicators of improved usefulness delivered to occupants.

Conversely, physiological stress burden, cognitive fatigue, sleep disruption, respiratory irritation, and environmental discomfort were treated as indicators of human-related sacrifices associated with indoor air management conditions and operational interventions.

These sacrifice-related conditions were conceptually aligned with sacrificed comfort (C_{fs}), sacrificed awareness (A_{ws}), and broader human-related burdens experienced during exposure to unfavourable indoor environmental conditions.

Environmental disruption, intervention intrusiveness, and occupant inconvenience associated with indoor air management activities were additionally evaluated as indicators of convenience-related usefulness and sacrifice dimensions within the value-delivery framework.

These conditions were linked conceptually to convenience gained (C_v) and sacrificed convenience (C_{vs}), depending on whether indoor air management activities improved or disrupted occupants' ability to comfortably and efficiently perform routine activities within indoor spaces.

Salivary cortisol sampling was conducted across representative workdays using repeated sampling intervals designed to capture temporal variation in physiological stress regulation under different environmental and operational conditions.

Sampling procedures followed standardised collection protocols controlling for food intake, caffeine consumption, smoking behaviour, and sampling time consistency to minimise non-environmental variability in cortisol measurements.

Elevated physiological stress responses were treated as potential indicators that indoor environmental conditions and operational management practices were imposing hidden human-related sacrifices not adequately reflected through conventional productivity metrics alone.

Spirometry testing assessed forced expiratory volume (FEV_1), forced vital capacity (FVC), and peak expiratory flow rates using calibrated portable spirometry systems operated according to internationally recognised respiratory assessment guidelines.

Repeated respiratory measurements were incorporated to evaluate potential longitudinal variation in respiratory function associated with cumulative indoor pollutant exposure and differing ventilation conditions across participating buildings. Respiratory protection and preservation of pulmonary function were treated as indicators of usefulness delivered through safer and higher-quality indoor environmental conditions.

Inflammatory biomarkers, including C-reactive protein (CRP), interleukin-6 (IL-6), and tumour necrosis factor alpha (TNF-α), were periodically assessed within a stratified subsample of participants representing varying building typologies, exposure conditions, occupational roles, and vulnerability profiles.

Biomarker analysis was conducted using standardised laboratory procedures to evaluate systemic inflammatory responses potentially associated with prolonged indoor pollutant exposure and environmental stress conditions.

Increased inflammatory burden was treated as a potential indicator of physiological sacrifice associated with prolonged exposure to suboptimal indoor environmental conditions despite apparent operational productivity improvements.

Heart rate variability and blood oxygen saturation monitoring were additionally incorporated to assess physiological stress regulation, autonomic nervous system response, and oxygenation status under varying indoor environmental conditions.

Sleep quality indices were evaluated using validated sleep assessment instruments and wearable sleep-monitoring systems to examine potential relationships among indoor environmental exposure, physiological recovery, and occupant wellbeing. Improved physiological recovery and stable autonomic regulation were treated as indicators of usefulness-related gains associated with healthier indoor environmental conditions.

Cognitive-task batteries were administered quarterly to assess sustained attention, executive function, working memory, decision consistency, reaction time, and cognitive fatigue throughout the investigation period. Computerised neurocognitive assessments included psychomotor vigilance testing, Stroop interference testing, N-back working memory tasks, and sustained attention response tasks administered under standardised testing conditions.

These cognitive assessments were incorporated because cognitive performance preservation and mental functioning formed part of the usefulness-related dimensions within the value-delivery framework, whereas cognitive fatigue and mental burden represented potential human-related sacrifices associated with deteriorating indoor environmental conditions.

Within the conceptual value equation, preserved cognitive functioning was additionally treated as an indicator that indoor environmental quality and safety were supporting occupants' ability to function effectively without excessive mental burden or physiological strain.

The longitudinal integration of physiological, cognitive, environmental, exposure, and operational measurements enabled evaluation of whether productivity-oriented indoor air management strategies corresponded with proportional improvements in occupant-related usefulness outcomes or whether measurable physiological and cognitive deterioration emerged despite apparent operational productivity improvement.

This multidimensional measurement framework was considered particularly important because many occupant-related consequences associated with indoor environmental conditions may not be adequately captured through conventional operational productivity indicators alone.

The framework, therefore, enabled direct evaluation of whether increases in operational productivity were accompanied by corresponding improvements in comfort, convenience, awareness, air quality, safety, and broader occupant-related usefulness outcomes, or whether operational efficiency improvements occurred alongside increasing human-related sacrifices and declining value delivery.

Advanced Causal and Statistical Analysis

The analytical framework employed advanced longitudinal causal modelling approaches specifically designed to address repeated measurements, temporal dependency, endogeneity risk, and hierarchical environmental structures across occupants, buildings, and operational periods.

The analytical structure was additionally designed to evaluate whether increasing productivity within operational indoor air management systems corresponded with proportional increases in value delivery or whether measurable productivity–value decoupling emerged under real-world operational conditions.

Generalised estimating equations (GEE) were employed to model repeated longitudinal measurements while accounting for within-subject temporal correlation across occupants and buildings. Exchangeable and autoregressive covariance structures were evaluated using quasi-likelihood information criteria to identify optimal model specification.

This modelling approach enabled longitudinal evaluation of temporal relationships among productivity indicators, environmental conditions, exposure burden, occupant-related outcomes, and value-delivery measurements across the full 24-month investigation period.

Fixed-effects models were additionally employed to control for time-invariant building-level heterogeneity, including architectural configuration, baseline ventilation design, climatic conditions, organisational structure, and operational characteristics.

This analytical strategy was incorporated to reduce confounding arising from stable building characteristics that could independently influence both productivity and value-delivery measurements, irrespective of operational interventions implemented during the study period.

Difference-in-differences estimation was subsequently applied during naturally occurring organisational intervention periods. Buildings implementing ventilation reductions, maintenance restructuring, filtration modifications, energy-conservation strategies, or monitoring reductions were compared against matched buildings maintaining relatively stable operational conditions during corresponding time periods.

This quasi-experimental analytical structure enabled evaluation of whether productivity-oriented operational changes produced proportional improvements in occupant-related usefulness outcomes or whether measurable deterioration in value-delivery indicators emerged despite apparent operational efficiency gains.

Instrumental variable analysis utilised outdoor wind speed and ambient temperature as instruments influencing ventilation dynamics while remaining plausibly exogenous to many organisational and behavioural outcomes. Instrument relevance and model validity were evaluated using standard instrumental variable diagnostic procedures, including first-stage F-statistics and over-identification testing.

The central analytical objective involved quantifying the degree of alignment or decoupling between longitudinal changes in productivity and longitudinal changes in value delivery across buildings and intervention periods. A productivity–value decoupling coefficient was therefore computed as:

$$D = \frac{\Delta \text{Value}}{\Delta \text{Productivity}}$$

where ΔValue represented longitudinal change in composite value-delivery measurements, and ΔProductivity represented longitudinal change in productivity measurements across corresponding operational periods.

Values approaching 1 indicated proportional alignment between productivity improvement and value-delivery improvement, whereas values approaching 0 or negative values indicated increasing productivity–value decoupling, whereby productivity improved while value delivery remained stagnant or deteriorated.Longitudinal productivity trajectories were compared directly against value-delivery trajectories across buildings and intervention periods.

Particular emphasis was placed on evaluating whether productivity increases were accompanied by proportional increases in occupant-related usefulness outcomes, including indoor air quality improvement, exposure reduction, physiological protection, cognitive performance preservation, comfort, convenience, awareness, and safety.

Buildings demonstrating substantial productivity improvement together with proportional value-delivery improvement were classified as productivity–value aligned systems. In contrast, buildings exhibiting productivity improvement alongside stagnant or declining usefulness-related outcomes were classified as productivity–value decoupled systems.

In practical terms, these decoupled systems represented operational conditions in which organisations appeared increasingly productive because outputs increased or invested resources decreased, while occupants experienced limited improvement or deterioration in indoor environmental quality, wellbeing, comfort, cognitive functioning, safety, or exposure protection.

Multilevel regression modelling and longitudinal trajectory analysis were subsequently employed to evaluate the magnitude, direction, and temporal stability of these productivity–value relationships across varying organisational and environmental conditions.

Machine learning clustering algorithms, including Gaussian mixture models and hierarchical clustering, were subsequently employed to classify buildings into productivity-value aligned systems, weakly aligned systems, decoupled systems, and adversely coupled systems.

These analytical procedures enabled the identification of operational systems exhibiting strong alignment, partial alignment, measurable decoupling, or adverse coupling between productivity improvement and value delivery across the investigation period.

Overall, the methodological framework for Phase II was specifically designed to determine whether productivity-oriented indoor air management systems genuinely improved value delivery under real-world operational conditions or whether measurable productivity–value decoupling emerged despite apparent operational productivity gains.

Ethical Considerations and Contribution to Knowledge

The investigation was conducted in accordance with established ethical principles governing human-participant environmental health research, longitudinal physiological monitoring, and organisational observational studies. Ethical approval was obtained from the relevant institutional ethics review board prior to data collection.

All participants provided informed consent after receiving detailed explanations of study objectives, monitoring procedures, confidentiality protections, and withdrawal rights. Participation remained entirely voluntary throughout the investigation.

Particular ethical attention was devoted to the collection of physiological, cognitive, and wearable exposure data because these involved potentially sensitive health-related and behavioural information. To protect participant privacy, all personal and organisational identifiers were removed during data processing, and encrypted participant codes were used throughout longitudinal analysis procedures.

The investigation also aimed to minimise participant burden during repeated monitoring activities. Physiological assessments, wearable exposure monitoring, cognitive evaluations, and environmental surveys were therefore designed to minimise disruption to participants' daily activities while maintaining scientific validity. All physiological assessments used non-invasive or minimally invasive procedures conducted by appropriately trained personnel.

Importantly, the investigation avoided intentionally exposing participants to harmful indoor environmental conditions. Instead, the quasi-experimental design leveraged naturally occurring operational conditions and organisational interventions already taking place within participating buildings. This preserved ecological validity while reducing ethical concerns associated with deliberate environmental manipulation.

The investigation contributes to knowledge by advancing understanding of productivity–value relationships within real-world indoor air management systems. It introduces an integrated productivity–value analytical framework capable of examining whether apparent productivity gains correspond with proportional improvements in occupant-related usefulness outcomes relative to the sacrifices and invested resources incurred during operational indoor air management activities.

Methodologically, the study integrates longitudinal environmental monitoring, physiological assessment, cognitive performance evaluation, operational productivity analysis, and causal inference modelling within a unified analytical structure.

Methods for Research Question 3 (Phase III):

Overview

The third phase of the investigation adopted a longitudinal mixed-methods intervention design. The phase aimed to design, implement, deploy, and evaluate an AI-based mobile decision-support framework. The framework was intended specifically to enhance practitioners' cognitive capability for sound judgement, decision-making, and action in value-oriented indoor air management problem diagnosis and solving.

Building upon the theoretical foundations established in Phases I and II, this phase was designed to investigate whether cognitive capability enhancement through AI-assisted reasoning support can improve value-oriented reasoning under conditions characterised by uncertainty, complexity, incomplete information, and competing stakeholder demands.

Unlike conventional indoor air management systems that primarily focus on operational efficiency, environmental monitoring automation, predictive analytics, or rapid intervention throughput, the present framework was designed fundamentally as a cognitive capability enhancement system. The framework was intended to support practitioners' reasoning processes during complex indoor air management activities.

The methodological foundation of the investigation recognised that indoor air management challenges may involve not only the availability of environmental data and analytical tools, but also practitioners' ability to cognitively process, interpret, integrate, prioritise, and operationalise complex environmental and stakeholder-related information. The investigation, therefore, examined how such cognitive processes influence alignment between productivity improvement and value delivery under real-world operational conditions.

Accordingly, the investigation examined whether practitioners operating under cognitively demanding conditions rely increasingly upon operationally visible and cognitively accessible indicators such as intervention speed, maintenance throughput, cost reduction, labour efficiency, and monitoring quantity during judgement and decision-making processes.

The investigation additionally examined how attention allocated to occupant-related, environmental, and stakeholder-related factors associated with value delivery may vary under such conditions. These factors included long-term health protection, comfort, awareness, safety, cognitive performance preservation, and exposure reduction.

Consequently, Phase III was designed to evaluate whether AI-assisted reasoning support can strengthen value-oriented judgement, decision-making, and action during indoor air management problem diagnosis and solving. Particular emphasis was placed on evaluating whether AI-assisted reasoning support improves practitioners' ability to enhance both productivity and value delivery during indoor air management problem diagnosis and solving.

The investigation additionally examined whether AI-assisted reasoning support reduces the likelihood that practitioners incorrectly interpret productivity improvement as evidence of proportional improvement in value delivery under conditions characterised by uncertainty, complexity, incomplete information, and competing stakeholder demands.

Experimental Indoor Air Management Scenarios Under Real-World ConditionsThe evaluation of the AI-supported cognitive capability enhancement framework was conducted within the same 16 healthcare, educational, office, and residential buildings previously examined during Phase II. These buildings had already undergone longitudinal environmental and operational characterisation during the earlier phase of the investigation.

The Phase III investigation was subsequently conducted during naturally occurring indoor air management activities and operational situations emerging across these buildings throughout the 12-month intervention period. Rather than relying on artificial laboratory simulations, practitioner reasoning and operational decision-making were evaluated under real-world indoor environmental conditions.

These situations included ventilation inadequacy, transient pollutant exposure events, filtration adjustment conflicts, thermal discomfort complaints, maintenance constraints, energy-conservation interventions, and operational budget pressures.

Many operational situations involved incomplete environmental information, uncertain pollutant source attribution, delayed environmental feedback, and competing stakeholder priorities. These real-world operational conditions formed the contextual basis within which practitioner reasoning, decision-making, and operational actions were examined throughout Phase III.

The inclusion of such conditions was informed by findings from Phases I and II, which established the importance of uncertainty, complexity, and stakeholder heterogeneity in influencing productivity–value reasoning during indoor air management problem diagnosis and solving.

Practitioner responses during these operational situations were subsequently examined throughout the intervention study to evaluate environmental interpretation, uncertainty management, stakeholder-related reasoning, and operational decision-making under cognitively demanding conditions.

Operational decisions generated during these real-world situations were additionally evaluated against independently reviewed multidisciplinary reference assessments developed by ventilation engineers, indoor air quality specialists, occupational hygienists, and healthy building professionals.

These comparisons enabled assessment of diagnostic quality, intervention appropriateness, stakeholder-related considerations, and broader value-delivery implications associated with practitioner decision-making during indoor air management activities.

AI-Supported Cognitive Capability Enhancement Design

The intervention study was conducted over a continuous 12-month deployment period involving a purposive subsample of 60 indoor air management practitioners drawn from the organisations and operational environments participating in Phase II. This subsampling approach was adopted to maintain methodological continuity across phases while ensuring operational feasibility within the time and resource constraints of the doctoral investigation.

Participants included ventilation engineers, facility managers, indoor air quality investigators, occupational hygienists, environmental consultants, sustainability specialists, and building operations personnel routinely engaged in operational indoor air management activities within the participating buildings. The participant pool, therefore, represented practitioners already operating within the real-world productivity–value conditions established in the experimental operational scenarios.

Participants were randomly assigned into intervention and control groups using stratified block randomisation procedures, controlling for professional experience, baseline diagnostic capability, organisational role, and building typology.

Thirty participants were equipped with the AI-based mobile cognitive capability enhancement framework deployed on smartphones and tablets, while the remaining 30 participants continued conventional operational practice without AI-assisted cognitive support.

Prior to commencement of the 12-month intervention period, participants assigned to both the AI-supported group and the conventional-practice group underwent a 4-week baseline assessment phase. The assessments evaluated diagnostic accuracy, professional experience, uncertainty tolerance, and operational reasoning capability.

This procedure was conducted to determine whether statistically significant differences existed between the two groups before the intervention period began. The assessment additionally ensured that both groups started the longitudinal intervention study from reasonably comparable baseline conditions.

The intervention structure was designed to evaluate whether repeated interaction with the AI-supported framework influenced practitioners' ability to sustain reflective reasoning, uncertainty management, stakeholder integration, causal interpretation, and value-oriented judgement during real-world indoor air management activities.

Cognitive capability enhancement was not operationalised merely as increased analytical speed or increased environmental information access. Instead, it was operationalised as improved practitioner capacity to distinguish among output quantity, invested resources, usefulness gained, sacrifices incurred, and overall value delivery under conditions characterised by uncertainty, complexity, and stakeholder heterogeneity.

Accordingly, the intervention study examined whether AI-assisted reasoning support influenced the quality, consistency, and value-oriented nature of judgement, decision-making, and operational action during indoor air management problem diagnosis and solving.

Development of the AI-Based Mobile Cognitive Capability Enhancement Framework

The AI-based mobile cognitive capability enhancement framework was developed using an interdisciplinary methodological architecture. The framework integrated indoor air quality science, cognitive systems engineering, behavioural decision theory, human-centred artificial intelligence, explainable machine learning, environmental exposure science, and value-oriented reasoning principles. The value-oriented reasoning principles were established during Phases I and II of the study.

The framework was developed specifically to support practitioner reasoning during the real-world operational situations established in the experimental indoor air management scenarios.

Phase I provided the behavioural and cognitive investigation framework for examining how uncertainty, complexity, and stakeholder heterogeneity influence productivity–value interpretation during indoor air management problem diagnosis and solving.

Phase II subsequently extended this investigation into longitudinal real-world operational environments to examine productivity–value relationships under varying indoor environmental conditions.

Phase III, therefore, operationalised these earlier findings within an AI-assisted intervention framework designed to support value-oriented judgement, decision-making, and operational action during cognitively demanding indoor air management activities.

The development process incorporated iterative user-centred design procedures involving pilot testing sessions with indoor air management practitioners participating in the Phase II operational environments.

Pilot testing incorporated repeated usability evaluation, reasoning-sequence analysis, interface refinement, and operational simulation exercises conducted under representative indoor air management conditions.

This iterative design strategy was implemented to ensure that the framework remained operationally usable under field conditions characterised by uncertainty, incomplete information, time pressure, and competing stakeholder demands.

The framework was deployed on smartphones and tablets operating within Android and iOS environments to support accessibility during real-world field-based operational activities occurring across the participating buildings.

This deployment structure enabled practitioners to interact with the framework directly during routine operational events, including ventilation inadequacy, occupant complaints, pollutant spikes, filtration adjustments, thermal discomfort situations, and maintenance interventions examined previously within the experimental operational scenarios.

The framework was not designed to replace human judgement or independently automate environmental decision-making. Instead, artificial intelligence was operationalised as a cognitive capability enhancement mechanism.

The framework was designed to support practitioner reflective reasoning, uncertainty interpretation, stakeholder integration, causal analysis, and value-oriented judgement during cognitively demanding operational conditions. The framework, therefore, functioned as a structured reasoning-support environment while maintaining practitioner responsibility throughout the operational decision-making process.

This distinction was considered methodologically important because many existing AI-supported operational systems prioritise automation efficiency, rapid recommendation generation, and throughput optimisation while providing comparatively limited support for reflective reasoning and cognitive engagement.

The framework was therefore intentionally designed to preserve practitioner cognitive involvement throughout operational reasoning activities. Recommendations generated by the framework required practitioner evaluation, interpretation, and justification prior to implementation.

These design procedures were incorporated to reduce passive automation dependence during operational indoor air management activities conducted across the participating buildings.

The framework integrated five interdependent cognitive support modules comprising environmental interpretation support, uncertainty interpretation support, value-oriented reasoning support, stakeholder integration support, and reflective decision-guidance support.

Each module was designed specifically to address cognitive limitations identified during Phase I, together with productivity–value reasoning behaviours examined during Phase II.

The environmental interpretation module continuously integrated environmental monitoring data streams established during Phase II. These included particulate matter concentrations, ventilation effectiveness, airflow behaviour, thermal conditions, carbon dioxide accumulation, pollutant exposure trajectories, occupancy fluctuations, and transient environmental instability.

Real-time visualisation interfaces and trend-comparison functions were incorporated to support practitioner interpretation of pollutant dynamics and longer-term environmental implications during operational indoor air management activities.

The uncertainty interpretation module incorporated Bayesian probabilistic modelling to quantify uncertainty associated with pollutant source attribution, ventilation performance, environmental measurements, and predicted intervention outcomes.

Under elevated uncertainty conditions, the framework generated prompts encouraging additional reflective evaluation before operational decisions were implemented. Probabilistic confidence intervals and uncertainty visualisation outputs were additionally incorporated to support practitioner interpretation of environmental uncertainty during operational reasoning activities.

The value-oriented reasoning module was grounded explicitly in the conceptual value framework operationalised throughout the investigation. The module structured practitioner evaluation of comfort, convenience, awareness, environmental quality, intervention quantity, safety outcomes, financial cost, cognitive burden, operational disruption, and stakeholder-related sacrifices incurred during indoor air management activities.

Comparative reasoning prompts were additionally incorporated to support practitioner distinction between productivity-related operational improvement and broader value-delivery implications affecting occupants and stakeholders.

The stakeholder integration module continuously prompted practitioners to evaluate how operational decisions affected different stakeholder groups, particularly vulnerable occupants whose health, comfort, cognitive performance, or safety conditions may not be immediately visible through conventional productivity indicators.

Vulnerability-weighting procedures were additionally incorporated to support evaluation of whether operational interventions disproportionately affected high-risk occupant groups, including elderly individuals, immunocompromised occupants, children, and cognitively demanding professional populations.

The reflective decision-guidance module structured practitioner reasoning sequences by encouraging causal interpretation, uncertainty reflection, long-term consequence evaluation, and explicit comparison between productivity improvement and value-delivery implications during operational decision-making activities.

Explainable artificial intelligence architecture was incorporated throughout the framework to ensure that recommendations, uncertainty estimates, environmental interpretations, and value-oriented reasoning prompts remained transparent and interpretable throughout practitioner interaction with the system.

This explainability structure was incorporated to support practitioner trust, preserve reflective engagement, and reduce passive acceptance of AI-generated recommendations during cognitively demanding operational situations.

Operationalisation of Cognitive Capability Enhancement

During deployment of the AI-supported framework, Phase III operationalised cognitive capability enhancement within the context of indoor air management problem diagnosis and solving under real-world operational conditions. Cognitive capability was not represented solely through knowledge acquisition, procedural memory, intervention speed, or increased environmental information access.

Instead, it was operationalised as practitioners' ability to interpret environmental complexity, integrate competing stakeholder needs, manage uncertainty, distinguish productivity improvement from value delivery, and sustain sound judgement, decision-making, and operational action during cognitively demanding indoor air management activities.

Accordingly, cognitive capability enhancement was operationalised multidimensionally through repeated assessment of diagnostic accuracy, uncertainty interpretation quality, causal reasoning quality, heuristic resistance, stakeholder integration capability, value-oriented reasoning consistency, cognitive flexibility, and decision quality.

These assessments were conducted during operational indoor air management activities occurring across the participating buildings. The measurements were incorporated to evaluate whether AI-assisted reasoning support influenced practitioners' ability to sustain reflective and value-oriented reasoning under the uncertainty-intensive operational conditions established previously in the experimental indoor air management scenarios.

Diagnostic accuracy was operationalised as the degree of agreement between practitioner-generated diagnoses and independently validated multidisciplinary reference diagnoses established using structured expert-review procedures. Evaluation scenarios included pollutant source attribution, ventilation failure interpretation, exposure pathway identification, and intervention prioritisation under uncertain environmental conditions.

Value-oriented reasoning consistency was evaluated using structured analytical scoring systems. These systems examined practitioners' ability to integrate usefulness-related outcomes, stakeholder impacts, sacrifices incurred, uncertainty conditions, long-term consequences, and safety implications during operational decision-making activities. Scoring procedures were conducted independently by trained evaluators blinded to participant intervention assignment.

The methodological framework additionally examined whether practitioners using the AI-supported framework demonstrated improved ability to distinguish among reductions in invested resources, productivity improvement, usefulness-related improvement, and overall value delivery. These evaluations were conducted during operational reasoning activities involving uncertainty, complexity, and competing stakeholder demands.

Heuristic dependence was assessed through behavioural analysis of decision pathways, omission bias frequency, information-processing duration, uncertainty consultation frequency, and reliance upon cognitively accessible operational indicators such as intervention speed, maintenance throughput, and operational cost reduction.

Eye-tracking analysis using wearable Tobii Pro Glasses 3 systems operating at 100 Hz was additionally conducted during selected indoor air management problem-solving sessions involving a representative practitioner subsample. This procedure was incorporated to evaluate attentional allocation patterns during uncertainty-intensive operational reasoning activities while maintaining operational feasibility within the doctoral investigation.

Cognitive flexibility was further assessed using adaptive probabilistic reasoning tasks involving dynamically changing environmental conditions. This assessment enabled evaluation of whether practitioners appropriately revised reasoning pathways in response to new environmental evidence during operational decision-making activities.

Real-Time Behavioural and Environmental Data Integration

Concurrently with the operationalisation of cognitive capability enhancement, the AI-supported framework continuously integrated environmental, behavioural, physiological, and operational data streams throughout the intervention period.

Environmental datasets were synchronised directly with the monitoring infrastructure established during Phase II. These datasets included pollutant concentrations, airflow effectiveness, thermal conditions, occupancy variation, ventilation dynamics, and cumulative exposure conditions across the participating buildings.

Environmental measurements were integrated at one-minute intervals to preserve the temporal resolution associated with transient pollutant events and rapidly changing operational conditions. Real-time environmental interpretation dashboards were incorporated into practitioner mobile interfaces to support operational reasoning during indoor air management activities conducted within the participating buildings.

Simultaneously, behavioural interaction logs captured practitioner engagement patterns with the AI-supported framework. These logs included information-search behaviour, uncertainty consultation frequency, recommendation revision behaviour, reasoning-sequence patterns, stakeholder evaluation frequency, and reflective reasoning duration during operational decision-making activities.

The methodological framework examined whether practitioners increasingly engaged in reflective and value-oriented reasoning rather than relying primarily upon operationally visible and cognitively accessible indicators alone.

Particular emphasis was placed on evaluating whether AI-assisted reasoning support influenced judgement quality, uncertainty interpretation, stakeholder-related evaluation, and operational decision-making under complex indoor environmental conditions.

The framework additionally examined whether repeated interaction with AI-assisted reasoning support influenced practitioner susceptibility to heuristic simplification, omission bias, and premature closure during environmental interpretation activities.

Longitudinal behavioural analysis was further conducted to evaluate whether repeated AI-assisted reflective reasoning contributed to sustained changes in practitioner cognitive behaviour throughout the intervention period.

Physiological and Cognitive Outcome Measurements

In addition to behavioural reasoning analysis and operational decision-monitoring, Phase III incorporated objective physiological and cognitive performance measurements throughout the intervention period.

These measurements were collected from both the intervention group using the AI-supported framework and the control group continuing conventional operational practice without AI-assisted support. The measurements were incorporated to strengthen scientific robustness and reduce dependence on subjective self-reporting alone.

Cognitive-task batteries assessed sustained attention, executive function, working memory, uncertainty tolerance, probabilistic reasoning capability, cognitive flexibility, and decision consistency.

Computerised assessments included psychomotor vigilance testing, Stroop interference testing, N-back working memory tasks, and probabilistic judgement tasks. These assessments were designed specifically to evaluate reasoning performance under uncertainty-intensive operational conditions.

Assessment sessions were conducted quarterly throughout the 12-month deployment period. This longitudinal structure enabled evaluation of temporal variation in cognitive performance throughout the intervention study.

Physiological measurements included heart rate variability, electrodermal activity, and salivary cortisol assessment during cognitively demanding indoor air management tasks. These measurements were incorporated to enable objective evaluation of physiological stress regulation, cognitive workload, and adaptive response under uncertainty-intensive operational conditions.

Heart rate variability analysis focused on vagal regulation associated with adaptive cognitive control during uncertainty-intensive reasoning activities. Electrodermal activity measurements enabled quantification of physiological arousal associated with cognitive stress during operational interpretation tasks.

Salivary cortisol assessment was additionally incorporated to evaluate temporal variation in physiological stress response during prolonged operational decision-making activities.

The longitudinal integration of physiological and cognitive measurements enabled objective comparison of cognitive performance, physiological stress regulation, and adaptive response patterns between practitioners using the AI-supported framework and practitioners continuing conventional operational practice throughout the intervention period.

Advanced Statistical and Causal Analysis

The analytical framework employed advanced longitudinal statistical and causal modelling approaches designed to evaluate whether AI-assisted cognitive capability enhancement influences cognitive capability, judgement quality, decision-making quality, action–value alignment, and productivity–value misclassification risk during indoor air management problem diagnosis and solving under real-world operational conditions.

The analytical structure aligned directly with Research Question 3, which examined whether AI-assisted cognitive capability enhancement improves value-oriented judgement, decision-making, and operational action under conditions characterised by uncertainty, complexity, incomplete information, and competing stakeholder demands.

Generalised estimating equations (GEE) were used to analyse repeated measurements collected from practitioners throughout the 12-month intervention period. Mixed-effects models additionally accounted for differences among practitioners and the 16 participating buildings.

Together, these statistical approaches enabled longitudinal comparison between practitioners using the AI-supported framework and practitioners continuing conventional indoor air management practice without AI-assisted support.

The primary analytical framework evaluated temporal differences between the intervention and control groups across five principal outcome domains: cognitive capability, judgement quality, decision quality, action–value alignment, and productivity–value misclassification risk.

Cognitive capability scores were derived from composite cognitive-task assessments, including uncertainty interpretation, probabilistic reasoning, cognitive flexibility, stakeholder integration capability, and decision consistency.

Judgement quality and decision quality were evaluated using independently reviewed multidisciplinary reference assessments developed by ventilation engineers, occupational hygienists, indoor air quality specialists, and healthy building professionals.

Action–value alignment analysis evaluated the extent to which practitioner operational actions remained consistent with broader value-delivery considerations, including occupant wellbeing, exposure reduction, safety, comfort, awareness, long-term health protection, and stakeholder-related consequences under uncertain operational conditions.

Productivity–value misclassification risk was evaluated using structured analytical scoring procedures, examining whether practitioners incorrectly interpreted productivity improvement as evidence of proportional improvement in value delivery.

The probability of productivity–value misclassification was modelled as:

P(Misclassification) = *f* (AI Assistance, Cognitive Capability, Uncertainty, Complexity, Stakeholder Heterogeneity)

Structural equation modelling was subsequently employed to evaluate mediation pathways linking AI-assisted cognitive capability enhancement, judgement quality, decision-making behaviour, operational action, and value-delivery outcomes. The primary mediation pathway was conceptualised as:

AI Framework→Cognitive Capability→Decision Quality→Value Delivery

These analytical procedures enabled evaluation of both the null and alternative hypotheses concerning whether AI-assisted cognitive capability enhancement significantly improves value-oriented reasoning and reduces productivity–value misclassification relative to conventional operational practice.

Bayesian hierarchical modelling was additionally employed to estimate practitioner-specific cognitive adaptation trajectories throughout the intervention period. Difference-in-differences estimation was further employed to compare pre-intervention and post-intervention changes between intervention and control groups while controlling for environmental and operational variation.

To strengthen methodological robustness, the framework incorporated cross-validation, temporal stability analysis, sensitivity testing, bootstrapped confidence interval estimation, missing-data imputation, inter-rater reliability assessment, adversarial robustness testing, reproducible computational workflows, explainable artificial intelligence evaluation procedures, and independent auditing protocols for algorithmic fairness, recommendation consistency, and calibration drift monitoring.

Ethical Considerations and Contribution to Knowledge

The Phase III investigation was conducted in accordance with established ethical principles governing human-participant behavioural research, AI-assisted decision-support systems, physiological monitoring, and longitudinal occupational studies.

Ethical approval was obtained from the relevant institutional ethics review board prior to participant recruitment and intervention deployment. All participants provided informed consent following detailed explanation of study objectives, AI-framework functionality, monitoring procedures, confidentiality protections, and withdrawal rights. Participation remained voluntary throughout the investigation.

Particular ethical attention was devoted to the deployment of the AI-supported cognitive capability enhancement framework because the investigation involved continuous behavioural interaction logging, physiological monitoring, cognitive assessments, and operational decision-tracking activities. To minimise privacy and occupational risk, all participant identifiers, organisational records, and operational decision logs were anonymised during data processing and analysis using encrypted participant codes.

The framework was intentionally designed as a reasoning-support system rather than an autonomous decision-making system. Practitioners therefore retained full responsibility for operational judgement, decision-making, and intervention implementation throughout the investigation period. AI-generated recommendations required practitioner interpretation prior to implementation to reduce passive automation dependence and preserve reflective cognitive engagement.

The investigation additionally incorporated algorithmic auditing, explainability evaluation, calibration drift monitoring, and fairness assessment procedures to minimise systematic bias and inconsistent operational guidance across practitioners and environmental conditions.

The study contributes to knowledge by advancing understanding of how AI-assisted cognitive capability enhancement may influence value-oriented indoor air management problem diagnosis and solving under real-world conditions characterised by uncertainty, complexity, incomplete information, and competing stakeholder demands.

Methodologically, the investigation integrates longitudinal environmental monitoring, behavioural reasoning analysis, physiological assessment, cognitive-performance evaluation, explainable artificial intelligence, and advanced causal modelling within a unified analytical structure.

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Research Findings

Findings for Research Question 1 (Phase I):

Overview

Across the entire dataset, increasing environmental complexity, informational uncertainty, and stakeholder heterogeneity were consistently associated with declining diagnostic accuracy, increased cognitive workload, greater heuristic dependence, higher productivity misclassification, and stronger value interpretation deviation.

These findings remained statistically significant across multilevel mixed-effects modelling, structural equation modelling, bootstrapped robustness analyses, adversarial perturbation testing, and repeated-measures stability analyses.

Most importantly, the findings demonstrated that practitioners operating under cognitively demanding operational conditions increasingly relied upon operationally visible and cognitively accessible indicators such as intervention speed, maintenance throughput, operational cost reduction, labour reduction, and output quantity when making judgements, decisions, and operational actions.

Under these conditions, practitioners increasingly interpreted reductions in invested resources, particularly time expenditure, operational cost, labour effort, and procedural complexity, as evidence of productivity improvement even when measurable operational output remained unchanged or usefulness-related outcomes did not improve proportionally.

Simultaneously, practitioners increasingly assumed that perceived productivity improvement automatically implied proportional improvement in value delivery during indoor air management problem diagnosis and solving activities. This occurred despite limited evaluation of whether usefulness gained actually outweighed the sacrifices incurred by occupants, organisations, and other stakeholders.

These behavioural distortions became substantially stronger under conditions involving high uncertainty, delayed environmental feedback, incomplete information, and competing stakeholder needs.

The findings therefore demonstrated that environmental complexity, informational uncertainty, and stakeholder heterogeneity causally increased the probability that practitioners misclassified reductions in invested resources as productivity gains and subsequently misinterpreted productivity gains as evidence of improved value delivery.

More specifically, practitioners operating under uncertainty-intensive operational conditions increasingly relied upon simplified operational reasoning pathways. These pathways prioritised rapidly measurable and organisationally reinforced indicators over multidimensional evaluation of usefulness gained relative to sacrifices incurred.

Under these conditions, practitioners demonstrated a greater tendency to interpret lower operational expenditure, reduced labour allocation, simplified intervention procedures, and faster operational completion as evidence of productivity improvement.

This occurred despite limited proportional improvement in pollutant mitigation effectiveness, occupant-related usefulness outcomes, or broader stakeholder-related value delivery.

These behavioural distortions became especially pronounced during operational situations involving delayed environmental feedback, uncertain pollutant source attribution, and competing stakeholder needs.

The findings therefore demonstrated a clear causal pathway linking cognitively demanding operational conditions to productivity–value confusion during indoor air management problem diagnosis and solving activities.

Behavioural Experimental Evaluation

Participant Characteristics and Behavioural Dataset: The repeated behavioural assessment framework generated a large multidimensional dataset comprising 742 completed simulation sessions, 31,864 operational decisions, 112,400 interaction logs, 18.7 million eye-tracking fixation records, 6,540 minutes of think-aloud verbal reasoning recordings, and approximately 1.2 terabytes of integrated behavioural, physiological, and environmental data.

The experimental conditions generated realistic operational indoor air management scenarios involving ventilation inadequacy, pollutant exposure events, mould contamination, energy-saving conflicts, thermal discomfort complaints, filtration optimisation disputes, and competing stakeholder priorities.

Participants demonstrated strong engagement throughout the experimental investigation. Mean interaction frequency reached 152.4 ± 27.8 interface interactions per session. Mean reasoning duration per operational decision reached 103.6 ± 24.5 seconds under moderate operational conditions and increased substantially under high-complexity conditions.

These findings indicated that the experimental environment successfully generated cognitively demanding operational situations requiring sustained judgement, interpretation, decision-making, and operational action.

Importantly, behavioural interaction patterns demonstrated that practitioners did not merely experience increased operational difficulty under cognitively demanding conditions. Instead, the findings indicated progressive shifts in how practitioners interpreted productivity and value delivery during indoor air management activities.

As operational conditions became more uncertain and complex, practitioners increasingly prioritised operationally visible indicators that were rapidly measurable, easier to justify organisationally, and cognitively less demanding to interpret during time-sensitive decision-making situations.

Effects of Environmental Complexity on Judgement and Decision-Making:
Environmental complexity exerted a substantial negative effect on diagnostic accuracy, reasoning quality, and operational decision consistency. Under low-complexity conditions, mean diagnostic accuracy reached 82.7 ± 7.9%.

However, under high-complexity conditions involving multiple interacting pollutant sources, delayed intervention effects, and dynamically changing operational variables, diagnostic accuracy declined to 63.4 ± 10.6% ($p < 0.001$).

High-complexity operational conditions additionally produced 41.8% longer decision-processing duration, 33.6% greater omission bias frequency, and 37.2% greater reliance upon operational simplification heuristics. Participants increasingly prioritised variables that were easier to observe, quantify, and operationally justify during high-complexity conditions.

Operational indicators including intervention speed, operational expenditure, labour reduction, maintenance throughput, and output quantity became increasingly dominant during judgement, decision-making, and operational action.

Under these conditions, practitioners increasingly interpreted reductions in invested resources, particularly operational time, labour effort, procedural complexity, and financial expenditure, as evidence of productivity improvement even when measurable operational output remained unchanged or usefulness-related outcomes did not improve proportionally.

In contrast, multidimensional usefulness-related outcomes, including occupant comfort, awareness, long-term health protection, cognitive performance preservation, and safety implications, received progressively less attention as environmental complexity intensified. Eye-tracking analysis demonstrated substantial attentional narrowing under high-complexity conditions.

Mean fixation duration allocated towards operational throughput indicators increased from 19.6% under low-complexity conditions to 36.8% under high-complexity conditions ($p < 0.001$). Simultaneously, fixation duration allocated towards occupant-related consequences declined from 28.3% to 15.7% ($p < 0.001$).

These findings demonstrated that increasing environmental complexity substantially altered practitioner attentional allocation patterns during indoor air management activities.

Importantly, practitioners increasingly demonstrated a tendency to assume that perceived productivity improvement automatically implied proportional improvement in value delivery.

This behavioural pattern became particularly evident during scenarios involving reduced intervention duration and simplified operational procedures despite limited proportional improvement in pollutant mitigation effectiveness or occupant-related usefulness outcomes.

Effects of Informational Uncertainty: Informational uncertainty produced the strongest independent effect across nearly all behavioural and cognitive outcome variables. Scenarios involving missing environmental measurements, contradictory occupant reports, delayed sensor feedback, and uncertain pollutant source attribution generated substantial reductions in judgement quality and diagnostic reliability.

Under low-uncertainty conditions, mean diagnostic accuracy reached 79.8 ± 8.3%. Under high-uncertainty conditions, diagnostic accuracy declined to 58.9 ± 11.4% ($p < 0.001$). Decision quality scores similarly declined from 76.1 ± 9.2 to 54.7 ± 12.1 ($p < 0.001$).

Bayesian uncertainty indices strongly predicted behavioural distortion outcomes. High-uncertainty scenarios with posterior entropy values exceeding 0.70 produced significantly higher omission bias, reduced causal reasoning depth, greater heuristic simplification, and stronger productivity–value confusion.

Multilevel mixed-effects modelling demonstrated that informational uncertainty exerted the strongest independent effect on productivity misclassification ($\beta = 0.44$, $p < 0.001$).

Participants operating under uncertainty-intensive conditions increasingly prioritised operational certainty proxies such as lower operational cost, faster implementation, simpler intervention pathways, reduced labour requirements, and rapidly measurable environmental indicators.

Think-aloud protocol analysis demonstrated progressively greater use of cognitively simplifying reasoning phrases under uncertainty-intensive conditions. Common operational reasoning phrases included “faster implementation,” “least operational disruption,” “cost-effective solution,” and “rapid completion.”

These reasoning patterns indicated increasing reliance upon reductions in invested resources as proxy indicators for productivity improvement under uncertainty-intensive operational conditions.

In contrast, references to long-term occupant wellbeing, delayed health implications, awareness outcomes, stakeholder vulnerability, and multidimensional value-delivery considerations declined substantially under uncertainty-intensive operational conditions.

Practitioners increasingly demonstrated limited evaluation of whether the usefulness gained actually outweighed the sacrifices incurred by occupants, organisations, and other stakeholders during indoor air management interventions.

Effects of Stakeholder Heterogeneity: Stakeholder heterogeneity significantly increased cognitive burden and operational reasoning conflict during indoor air management activities. Scenarios involving competing stakeholder priorities generated significantly poorer value-oriented reasoning performance compared with operational scenarios involving relatively aligned stakeholder objectives.

Under low stakeholder heterogeneity conditions, value-oriented reasoning scores averaged 74.2 ± 8.7. Under high stakeholder heterogeneity conditions involving conflicts among energy efficiency, operational expenditure, occupant comfort, infection control, and long-term health protection, scores declined to 56.8 ± 11.9 ($p < 0.001$).

Participants increasingly prioritised operational efficiency indicators over multidimensional stakeholder consequences during high-conflict operational conditions. For example, 71.8% of participants prioritised energy-reduction objectives over occupant comfort preservation under operational budget pressure scenarios, while 64.3% selected lower-cost filtration interventions despite reduced protection for vulnerable occupants.

Importantly, practitioners operating under competing stakeholder demands increasingly demonstrated tendency to interpret lower operational expenditure and reduced intervention burden as evidence of productivity improvement.

Simultaneously, practitioners frequently assumed that these perceived productivity gains automatically implied proportional improvement in value delivery despite reduced occupant-related usefulness outcomes or increased stakeholder-related sacrifices.

These findings demonstrated that competing stakeholder priorities substantially intensified productivity–value confusion during indoor air management problem diagnosis and solving.

Combined Complexity–Uncertainty–Stakeholder Heterogeneity Effects: The combined complexity–uncertainty–stakeholder heterogeneity index (CUH_i) demonstrated strong predictive capability for behavioural distortion outcomes. Increasing CUH_i significantly increased productivity misclassification probability, value interpretation deviation, omission bias frequency, attentional narrowing, and heuristic dependence.

Mixed-effects regression modelling demonstrated odds ratios of 3.84 for productivity misclassification and 4.26 for value interpretation deviation, both statistically significant at $p < 0.001$. Interaction modelling further demonstrated that combined exposure to complexity, uncertainty, and stakeholder heterogeneity produced substantially greater behavioural distortion than isolated operational stressors independently.

More specifically, practitioners operating under combined high-complexity and high-uncertainty conditions increasingly relied upon simplified operational reasoning pathways that prioritised rapidly measurable and organisationally reinforced indicators over multidimensional evaluation of usefulness gained relative to sacrifices incurred.

Under these conditions, practitioners demonstrated greater tendency to interpret lower operational expenditure, reduced labour allocation, simplified intervention procedures, and faster operational completion as evidence of productivity improvement. This occurred despite limited proportional improvement in pollutant mitigation effectiveness, occupant-related usefulness outcomes, or broader stakeholder-related value delivery.

These behavioural distortions became especially pronounced during operational situations involving delayed environmental feedback, uncertain pollutant source attribution, and competing stakeholder needs.

The findings therefore demonstrated a clear causal pathway linking cognitively demanding operational conditions to productivity–value confusion during indoor air management problem diagnosis and solving activities.

This finding was scientifically important because it demonstrated that productivity–value confusion emerged most strongly under realistic operational conditions involving simultaneous uncertainty, complexity, and competing stakeholder demands rather than under isolated operational stressors alone.

Operationalisation of Cognitive Misclassification Constructs

Productivity Misclassification: The productivity misclassification index (MP_i) increased substantially under cognitively demanding operational conditions. Under low-complexity conditions, mean MP_i reached +0.18 ± 0.09. Under high-complexity and high-uncertainty conditions, mean MP_i increased to +0.61 ± 0.17 ($p < 0.001$).

Participants increasingly interpreted reductions in invested resources, particularly time expenditure, labour effort, operational expenditure, and procedural complexity, as evidence of productivity improvement even when objective intervention effectiveness remained unchanged or deteriorated.

Across 67.3% of high-pressure operational scenarios, participants interpreted reduced operational expenditure as productivity improvement despite no statistically significant improvement in indoor environmental quality, pollutant reduction effectiveness, or stakeholder-related usefulness outcomes.

Importantly, these behavioural patterns aligned closely with the attentional narrowing and heuristic simplification behaviours observed during the behavioural experimental evaluation.

Practitioners operating under cognitively demanding operational conditions increasingly relied upon indicators that were operationally visible and cognitively accessible when interpreting productivity improvement. These indicators included intervention speed, reduced labour allocation, maintenance throughput, and operational cost reduction.

In contrast, comparatively less cognitive attention was allocated towards multidimensional evaluation of usefulness gained relative to sacrifices incurred by occupants, organisations, and other stakeholders.

These findings demonstrated that operationally visible reductions in invested resources strongly influenced productivity interpretation under cognitively demanding conditions. The findings additionally demonstrated acceptable construct stability and internal consistency across repeated operational scenarios involving varying uncertainty and complexity conditions.

Value Interpretation Deviation: Value interpretation deviation (MV_i) also increased substantially under cognitively demanding conditions. Under low-complexity conditions, mean MV_i reached +0.14 ± 0.07. Under high-complexity and high-uncertainty conditions, mean MV_i increased to +0.57 ± 0.16 ($p < 0.001$).

Participants frequently assumed that productivity improvement automatically implied proportional improvement in value delivery. This assumption remained highly prevalent under uncertainty-intensive operational conditions.

Structural equation modelling demonstrated that productivity misclassification significantly mediated value interpretation deviation, with a standardised indirect effect of 0.48 ($p < 0.001$).

More specifically, practitioners frequently assumed that lower operational expenditure, reduced intervention duration, simplified operational procedures, and reduced staffing requirements automatically implied broader improvement in stakeholder-related value delivery.

This assumption persisted despite limited proportional improvement in pollutant mitigation effectiveness, occupant comfort, long-term health protection, or awareness-related outcomes.

These behavioural distortions became substantially stronger during operational situations involving delayed environmental feedback, uncertain pollutant source attribution, and competing stakeholder needs.

These findings demonstrated that productivity misclassification directly contributed to broader distortion in value-delivery interpretation during indoor air management activities.

The MV_i construct additionally demonstrated stable behavioural differentiation across varying operational scenarios and participant groups, supporting its discriminative analytical capability within the investigation framework.

Cognitive and Behavioural Measurement

Cognitive Load and Physiological Stress: NASA-TLX cognitive workload scores increased substantially under cognitively demanding operational conditions. Mean cognitive workload increased from 41.8 ± 8.6 under low-complexity conditions to 74.5 ± 10.2 under high-complexity and high-uncertainty conditions ($p < 0.001$).

Heart rate variability analysis demonstrated progressive reductions in adaptive vagal regulation under cognitively demanding operational conditions. Electrodermal activity increased significantly during uncertainty-intensive scenarios, indicating elevated physiological stress response.

Participants operating under high-uncertainty conditions demonstrated 27.4% lower heart rate variability and 34.6% higher electrodermal response intensity compared with low-uncertainty conditions ($p < 0.001$).

These physiological findings demonstrated that cognitively demanding operational conditions substantially increased cognitive strain during indoor air management problem diagnosis and solving.

Importantly, increasing cognitive strain was accompanied by progressively greater reliance upon operationally visible and cognitively accessible indicators during judgement, decision-making, and operational action.

Participants operating under elevated cognitive workload conditions increasingly prioritised intervention speed, operational expenditure reduction, reduced labour allocation, maintenance throughput, and rapidly measurable operational outputs during environmental interpretation activities.

Simultaneously, practitioners demonstrated progressively reduced evaluation of multidimensional usefulness-related outcomes and stakeholder-related sacrifices under high cognitive workload conditions.

This included reduced consideration of occupant comfort, long-term health protection, awareness-related outcomes, vulnerable occupant consequences, and delayed exposure implications during indoor air management problem diagnosis and solving activities.

Eye-Tracking: Eye-tracking analysis revealed strong evidence of attentional narrowing and operational simplification behaviour. Participants increasingly allocated visual attention towards cost-related variables, throughput indicators, intervention speed metrics, and operational output quantity measures under cognitively demanding conditions.

Under high-uncertainty conditions, fixation duration towards operational indicators increased by 38.6%, while fixation duration towards occupant-related consequences declined by 29.4% ($p < 0.001$).

Heat-map concentration analysis demonstrated progressively narrower attentional distribution under increasing complexity and uncertainty. Participants increasingly focused attention on immediately measurable operational indicators while underweighting multidimensional usefulness-related outcomes.

These findings strongly supported the proposition that practitioners operating under cognitively demanding conditions increasingly prioritised variables that were cognitively accessible and operationally visible during judgement and decision-making.

More specifically, participants increasingly focused visual attention on indicators associated with reductions in invested resources, particularly operational cost reduction, reduced intervention duration, labour reduction, and simplified operational procedures.

In contrast, comparatively less visual attention was allocated towards indicators associated with long-term usefulness outcomes, stakeholder-related sacrifices, and broader value-delivery implications.

These attentional allocation patterns aligned closely with the productivity misclassification and value interpretation deviation findings observed throughout the behavioural investigation.

Participants increasingly interpreted reductions in invested resources as evidence of productivity improvement and subsequently assumed that perceived productivity improvement automatically implied proportional improvement in value delivery.

Think-Aloud Protocol: Natural language processing analysis demonstrated substantial changes in reasoning behaviour under cognitively demanding operational conditions. High-complexity and uncertainty-intensive scenarios produced greater heuristic language use, reduced causal reasoning depth, higher omission bias, and stronger operational simplification patterns.

Omission bias frequency increased from 14.7% under low-complexity conditions to 46.9% under high-complexity and high-uncertainty conditions ($p < 0.001$). Participants increasingly omitted discussion of long-term health implications, vulnerable occupant consequences, delayed exposure outcomes, and awareness-related considerations during operational reasoning activities conducted under cognitively demanding conditions.

Think-aloud protocol analysis additionally demonstrated increasing reliance upon simplified productivity-oriented reasoning pathways under uncertainty-intensive operational conditions.

Common reasoning phrases increasingly reflected emphasis on faster implementation, lower operational expenditure, reduced staffing requirements, simplified intervention procedures, and rapid operational completion.

These behavioural patterns indicated increasing tendency to interpret reductions in invested resources as evidence of productivity improvement during cognitively demanding operational situations.

Simultaneously, practitioners increasingly demonstrated limited verbal evaluation of whether usefulness gained actually outweighed sacrifices incurred by occupants, organisations, and other stakeholders.

These findings further supported the proposition that environmental complexity, informational uncertainty, and stakeholder heterogeneity progressively strengthened productivity–value confusion during indoor air management problem diagnosis and solving activities.

Statistical and Causal Analysis

Multilevel mixed-effects modelling demonstrated that environmental complexity, informational uncertainty, and stakeholder heterogeneity significantly impaired judgement quality, decision consistency, causal reasoning capability, and operational action quality during indoor air management activities.

Random intercept modelling additionally demonstrated meaningful contextual variation across countries, organisations, and professional disciplines, although the principal behavioural distortion patterns remained highly consistent across operational environments. Increasing environmental complexity, uncertainty, and competing stakeholder needs significantly increased the probability that practitioners interpreted reductions in invested resources as evidence of productivity improvement.

Under cognitively demanding conditions, practitioners increasingly relied upon operationally visible and cognitively accessible indicators such as operational cost reduction, reduced labour allocation, intervention speed, maintenance throughput, simplified operational procedures, and rapidly measurable operational outputs.

These distortions became substantially stronger under conditions involving incomplete environmental information, delayed operational feedback, uncertain pollutant source attribution, and competing stakeholder demands.

Structural equation modelling further demonstrated that environmental complexity, informational uncertainty, and stakeholder heterogeneity indirectly influenced productivity misclassification and value interpretation deviation through cognitive load, attentional narrowing, heuristic dependence, declining judgement quality, and poorer decision quality.

The structural model demonstrated excellent fit characteristics (CFI = 0.95, RMSEA = 0.038, SRMR = 0.041). Importantly, productivity misclassification significantly mediated value interpretation deviation.

Practitioners who increasingly interpreted reductions in invested resources as productivity gains were substantially more likely to assume that perceived productivity improvement automatically implied proportional improvement in value delivery.

This sequential causal pathway became especially pronounced during situations involving delayed environmental consequences, uncertainty-intensive environmental interpretation, and competing stakeholder needs.

Bootstrapping involving 10,000 repeated resamples demonstrated high stability across behavioural and causal modelling outcomes. Additional sensitivity analyses were subsequently conducted to further evaluate the robustness of the findings.

These analyses included adversarial perturbation testing, false discovery rate correction, cross-validation procedures, and temporal stability analyses. Collectively, the results demonstrated that the principal findings remained statistically significant across alternative model specifications, varying uncertainty conditions, and simulated operational perturbations.

Robustness analyses further demonstrated that productivity misclassification and value interpretation deviation patterns remained stable across professional groups, environmental scenarios, organisational conditions, and uncertainty levels.

Practical Interpretation for Real-World Context and Scientific Implications

The findings from Research Question 1 provided strong support for the alternative hypothesis (H_{11}) and rejected the null hypothesis (H_{01}). The investigation demonstrated that environmental complexity, informational uncertainty, and stakeholder heterogeneity had statistically significant effects on indoor air management practitioners during problem diagnosis and decision-making activities.

Specifically, these conditions significantly increased the probability that practitioners misclassified reductions in invested resources as productivity gains. The findings further demonstrated that practitioners subsequently misinterpreted productivity gains as proportional improvements in value delivery.

Importantly, the findings demonstrated that productivity–value confusion was not simply caused by insufficient technical knowledge or lack of environmental information alone. Instead, cognitively demanding operational conditions progressively reduced practitioners' ability to sustain reflective and value-oriented reasoning during judgement, decision-making, and operational action.

Practitioners operating under uncertainty-intensive conditions increasingly relied upon operationally visible and cognitively accessible indicators such as intervention speed, operational cost reduction, labour reduction, maintenance throughput, simplified procedures, and output quantity.

Under such conditions, reductions in invested resources were increasingly interpreted as evidence of productivity improvement even when pollutant mitigation effectiveness, occupant-related usefulness outcomes, and broader stakeholder-related value delivery did not improve proportionally.

The findings further demonstrated that productivity improvement and value delivery are not interchangeable constructs during indoor air management activities. Consequently, lower operational expenditure, faster implementation, simplified procedures, and reduced staffing requirements should not automatically be interpreted as evidence of successful indoor air management performance.

Scientifically, the investigation demonstrated a causal pathway linking environmental complexity, informational uncertainty, and stakeholder heterogeneity to productivity misclassification and subsequent value-delivery misinterpretation.

More broadly, the findings demonstrated that effective indoor air management requires not only technical competence and operational efficiency, but also sufficient cognitive capability for reflective and value-oriented reasoning under uncertainty-intensive conditions.

Findings for Research Question 2 (Phase II):

Overview

Phase II investigated the extent to which increases in operational productivity corresponded with, or became decoupled from, actual value delivery within indoor air management systems operating under real-world conditions.

Productivity was evaluated as increases in output relative to invested resources, while value delivery was evaluated as increases in usefulness gained relative to invested resources across environmental, physiological, cognitive, comfort, safety, and stakeholder-related outcomes.

Across the 24-month longitudinal investigation period, substantial divergence emerged between productivity trajectories and value-delivery trajectories across healthcare, educational, office, and residential buildings.

Overall, productivity and value delivery demonstrated only weak-to-moderate proportional association across many operational conditions. Increases in output per unit of invested resources frequently exceeded corresponding increases in usefulness gained per unit of invested resources.

Importantly, productivity and value delivery did not remain perfectly aligned even under conditions where reductions in invested resources were not strongly misclassified as productivity improvement.

Measurable productivity improvement often still deviated substantially from proportional value-delivery improvement due to environmental uncertainty, delayed exposure consequences, fluctuating operational conditions, competing stakeholder priorities, and the multidimensional nature of usefulness-related outcomes.

However, productivity–value decoupling became substantially greater when practitioners and operational systems increasingly interpreted reductions in invested resources as evidence of productivity improvement.

Buildings strongly prioritising operational cost reduction, labour reduction, simplified operational procedures, faster intervention completion, maintenance throughput, and energy-saving performance consistently demonstrated the largest productivity–value separation over time.

Many buildings demonstrated measurable increases in intervention throughput, reductions in operational expenditure, faster maintenance response time, reduced labour requirements, improved maintenance efficiency, and stronger energy-saving performance.

However, these productivity improvements frequently failed to correspond with proportional improvement in indoor air quality, cumulative exposure reduction, airflow effectiveness, physiological protection, cognitive performance preservation, environmental comfort, awareness-related outcomes, safety conditions, and broader occupant-related usefulness outcomes.

In several buildings, measurable productivity improvement was observed while occupant-related usefulness outcomes remained stagnant or progressively deteriorated.

The degree of productivity–value decoupling became progressively stronger under conditions involving delayed environmental feedback, uncertain pollutant source attribution, fluctuating occupancy conditions, budget constraints, incomplete information, and competing organisational priorities.

Importantly, the findings demonstrated that productivity–value confusion became operationally embedded within functioning indoor air management systems over time. Operational systems increasingly reinforced productivity-oriented indicators even when multidimensional value-delivery outcomes remained unchanged or deteriorated.

Overall, the findings demonstrated that increases in productivity did not necessarily correspond with proportional increases in value delivery. More importantly, confusing reduction in invested resources with genuine productivity improvement substantially amplified productivity–value decoupling across multiple operational contexts.

Longitudinal Field Investigation Findings

Building Characteristics and Operational Variation: Substantial environmental and operational heterogeneity was observed across the 16 participating buildings throughout the 24-month investigation period.

Healthcare facilities demonstrated the highest average ventilation rates and the greatest operational intensity due to infection-control requirements, continuously occupied zones, and high occupant turnover. Educational buildings exhibited the greatest temporal variability in occupancy and ventilation adequacy, particularly during peak academic periods.

Office environments demonstrated substantial variation in airflow distribution effectiveness and operational management strategies, while residential buildings exhibited highly variable pollutant generation associated with occupant activities, cooking practices, cleaning behaviour, and natural ventilation usage.

The extended longitudinal monitoring period successfully captured substantial temporal variation associated with occupancy redistribution, climatic fluctuations, equipment ageing, maintenance cycles, ventilation adjustments, organisational restructuring, and energy-conservation initiatives. Seasonal weather variation alone contributed to approximately 18.7% fluctuation in ventilation performance across naturally ventilated and mixed-mode buildings.

Importantly, these temporal variations demonstrated that productivity improvement and value delivery frequently diverged progressively over time under real-world operational conditions. Several buildings initially demonstrated relatively aligned productivity and value-delivery trajectories during the early monitoring phase.

However, increasing operational pressure, energy-conservation restructuring, labour optimisation, and maintenance simplification progressively widened the separation between productivity performance and occupant-related usefulness outcomes throughout the investigation period.

Across the investigation period, organisations increasingly implemented operational strategies designed to improve measurable productivity outcomes. These strategies included ventilation scheduling optimisation, reduced environmental monitoring frequency, simplified maintenance procedures, labour restructuring, energy-saving interventions, and reductions in operational expenditure associated with indoor air management activities.

Buildings implementing the most aggressive productivity-oriented restructuring demonstrated mean intervention throughput increases exceeding 30%, while operational cost per intervention decreased by approximately 20% to 25% across several office and educational buildings.

However, the findings demonstrated that these productivity gains frequently emerged primarily through reductions in invested resources rather than proportional improvement in usefulness gained relative to invested resources.

Buildings demonstrating the strongest emphasis on labour reduction, operational cost reduction, simplified intervention implementation, and maintenance throughput consistently demonstrated greater productivity–value decoupling throughout the longitudinal investigation period.

Importantly, buildings that maintained clearer distinction between genuine productivity improvement and simple reduction in invested resources generally demonstrated comparatively smaller productivity–value deviation over time.

In contrast, buildings that increasingly interpreted reductions in invested resources as evidence of productivity improvement demonstrated substantially larger separation between productivity trajectories and value-delivery trajectories.

Environmental Monitoring and Indoor Air Quality: Environmental monitoring demonstrated that improvements in operational productivity frequently failed to correspond with proportional improvement in indoor environmental quality.

Across multiple buildings, increasing operational efficiency occurred simultaneously with worsening pollutant accumulation, declining airflow effectiveness, and increasing cumulative occupant exposure burden.

Office buildings implementing energy-saving ventilation schedules demonstrated some of the clearest productivity–value decoupling patterns observed during the investigation.

Although these buildings demonstrated substantial reductions in energy expenditure and improved operational efficiency metrics, mean $PM_{2.5}$ concentrations increased by approximately 37.8% over the monitoring period, while effective air change rate declined from 4.9 ACH_e to 3.1 ACH_e. Simultaneously, peak carbon dioxide concentrations increasingly exceeded 1,900 ppm during high-density occupancy periods.

These findings demonstrated that substantial reductions in invested resources and measurable productivity-oriented operational gains did not necessarily correspond with proportional improvement in usefulness-related environmental outcomes.

Instead, the productivity trajectories increasingly diverged from the idealised productivity–value equality relationship observed conceptually within the investigation framework.

Educational buildings similarly demonstrated progressively deteriorating ventilation adequacy during productivity-oriented intervention periods. Carbon dioxide concentrations exceeded recommended thresholds during approximately 41.6% of occupied hours within several classrooms and lecture halls operating under reduced ventilation schedules. These deteriorating environmental conditions emerged despite measurable improvement in operational efficiency and maintenance throughput.

Residential environments demonstrated substantial episodic pollutant accumulation associated with reduced natural ventilation behaviour, energy-conservation practices, and variable airflow distribution. Mean VOC concentrations increased by approximately 28.7% during periods characterised by reduced window-opening behaviour and decreased effective airflow delivery.

Importantly, these deteriorating environmental conditions were frequently not reflected within conventional operational productivity indicators because intervention completion rates, labour efficiency, and maintenance throughput remained relatively stable or improved.

Healthcare facilities generally maintained superior nominal ventilation rates compared with the other building typologies. However, several healthcare environments demonstrated declining airflow effectiveness despite relatively stable airflow supply rates.

This finding proved scientifically important because it demonstrated that nominal ventilation quantity alone did not necessarily correspond with proportional pollutant removal effectiveness within occupant breathing zones.

In several healthcare environments, supplied air increasingly bypassed occupied microenvironments, resulting in worsening pollutant removal performance despite apparently acceptable productivity-oriented ventilation delivery metrics.

Collectively, these findings demonstrated that productivity-oriented operational management frequently prioritised operationally visible and organisationally reinforced indicators while giving comparatively less attention to effective pollutant removal performance and occupant-centred usefulness outcomes.

Importantly, the findings further demonstrated that the tendency to confuse reduction in invested resources with genuine productivity improvement substantially amplified productivity–value decoupling across multiple buildings and operational conditions.

Cumulative Exposure: Wearable exposure monitoring revealed substantial differences in cumulative exposure burden across buildings and intervention periods. Occupants within buildings demonstrating strong productivity–value decoupling experienced significantly greater cumulative pollutant exposure compared with occupants within buildings where productivity and value delivery remained comparatively more aligned.

Mean cumulative $PM_{2.5}$ exposure dose within productivity-oriented but environmentally deteriorating buildings reached approximately 418.6 µg·h/m³ compared with 233.4 µg·h/m³ within buildings demonstrating relatively stronger productivity–value alignment.

Similar exposure disparities emerged for VOCs and nitrogen dioxide concentrations, particularly within office and educational environments implementing reduced ventilation schedules, labour optimisation measures, simplified environmental management procedures, and operational cost reduction strategies.

Longitudinal exposure trajectories demonstrated progressive accumulation effects over time. Occupants spending prolonged durations within poorly ventilated environments exhibited increasingly elevated exposure burden despite ongoing organisational claims of improved operational efficiency and productivity enhancement.

This finding proved particularly important because operational productivity indicators frequently suggested successful environmental management performance while occupant-level usefulness outcomes and exposure-protection outcomes simultaneously deteriorated.

Importantly, buildings demonstrating the greatest productivity–value decoupling were also the buildings most likely to operationally reinforce reductions in invested resources as indicators of productivity success. These buildings demonstrated progressively widening divergence between output-oriented productivity indicators and occupant-related usefulness outcomes throughout the monitoring period.

The findings therefore demonstrated that productivity improvement alone provided an unreliable indicator of actual exposure protection and occupant-related usefulness outcomes under real-world indoor air management conditions.

More importantly, the findings demonstrated that confusing reduction in invested resources with genuine productivity improvement substantially intensified productivity–value decoupling and progressively weakened the proportional relationship between productivity trajectories and value-delivery trajectories over time.

Physiological and Human Outcome

Physiological Stress and Inflammatory Response: Longitudinal physiological analysis demonstrated progressively worsening physiological stress burden among occupants exposed to deteriorating environmental conditions within productivity-oriented operational environments. Occupants within buildings demonstrating the greatest productivity–value decoupling exhibited significantly elevated physiological stress indicators over time.

Salivary cortisol analysis demonstrated approximately 19.8% increase in mean physiological stress burden among occupants within high productivity–low value-delivery buildings across the 24-month investigation period.

These increases were strongly associated with elevated carbon dioxide accumulation, declining airflow effectiveness, increasing pollutant burden, and prolonged exposure duration.

Heart rate variability analysis similarly demonstrated progressive reductions in adaptive vagal regulation among occupants within environmentally deteriorating operational environments. Occupants within productivity–value decoupled buildings demonstrated approximately 23.7% lower mean heart rate variability relative to occupants within buildings where productivity and value delivery remained relatively aligned. Electrodermal response intensity also increased substantially during periods characterised by elevated pollutant accumulation and poor ventilation effectiveness.

Inflammatory biomarker analysis demonstrated progressively elevated CRP, IL-6, and TNF-α concentrations among occupants within buildings exhibiting increasing cumulative exposure burden. Mean IL-6 concentrations increased by approximately 31.4% among occupants exposed to prolonged reduced ventilation schedules and elevated particulate concentrations.

Importantly, the largest physiological deterioration patterns were consistently observed within buildings that most strongly reinforced reductions in invested resources, simplified maintenance procedures, labour optimisation, and operational cost reduction as indicators of productivity improvement.

These findings demonstrated that substantial productivity-oriented operational gains frequently coexisted with progressively worsening physiological sacrifice among occupants. In many buildings, operational productivity indicators continued improving while physiological protection outcomes simultaneously deteriorated.

This demonstrated that productivity improvement alone did not reliably correspond with proportional improvement in value delivery under real-world indoor air management conditions.

Importantly, these physiological deterioration patterns frequently emerged gradually over extended operational periods rather than immediately following intervention implementation.

Consequently, organisations frequently continued interpreting operational productivity gains as successful indoor air management performance while hidden physiological burden progressively accumulated among occupants.

The findings further demonstrated that buildings which increasingly confused reduction in invested resources with genuine productivity improvement exhibited substantially greater physiological burden accumulation compared with buildings maintaining clearer distinction between resource reduction and genuine value-oriented productivity improvement.

This pattern demonstrated that confusion between invested-resource reduction and productivity improvement substantially amplified productivity–value decoupling across human-related outcomes.

Respiratory Function: Repeated spirometry assessments demonstrated measurable deterioration in respiratory protection outcomes among occupants exposed to productivity-oriented but environmentally deteriorating indoor conditions.

Occupants within buildings characterised by elevated cumulative particulate exposure demonstrated significantly greater decline in FEV_1 trajectories over time compared with occupants within productivity–value aligned environments.

Mean FEV_1 decline reached approximately 4.7% among occupants within productivity–value decoupled buildings compared with approximately 1.3% among occupants within aligned buildings.

Respiratory irritation symptoms, throat discomfort, nasal irritation, sleep disturbance, and fatigue similarly increased substantially among occupants exposed to prolonged elevated pollutant burden and declining airflow effectiveness.

Importantly, several buildings demonstrating the largest reductions in operational expenditure and strongest maintenance-efficiency improvement simultaneously demonstrated the greatest respiratory protection deterioration over time.

These findings demonstrated that operational productivity gains achieved primarily through reductions in invested resources frequently failed to preserve proportional occupant-related usefulness outcomes.

The respiratory findings additionally demonstrated that productivity–value decoupling progressively intensified when operational systems increasingly prioritised intervention throughput, labour reduction, and operational simplification over sustained exposure protection effectiveness and long-term respiratory wellbeing.

These findings demonstrated that apparent operational productivity improvement frequently failed to preserve respiratory protection and occupant physiological wellbeing under real-world operational conditions.

Cognitive Performance: Cognitive-task assessments revealed substantial longitudinal variation in cognitive functioning across buildings and intervention periods.

Occupants within buildings demonstrating productivity–value decoupling exhibited progressively poorer sustained attention, slower reaction time, declining executive functioning, and greater cognitive fatigue throughout the investigation period.

Psychomotor vigilance testing demonstrated approximately 11.8% reaction-time slowing during periods characterised by elevated carbon dioxide accumulation and increasing particulate exposure burden.

N-back working memory performance similarly declined by approximately 9.6% among occupants within buildings implementing reduced ventilation schedules and simplified environmental management strategies.

Educational environments demonstrated particularly strong cognitive performance deterioration during high-density occupancy periods associated with elevated carbon dioxide accumulation and declining ventilation adequacy.

These findings were especially important because educational buildings frequently demonstrated improved operational productivity indicators despite worsening cognitive performance outcomes affecting students and staff.

Importantly, the buildings demonstrating the strongest productivity–value decoupling also demonstrated the greatest decline in cognitive performance preservation outcomes over time.

Buildings increasingly interpreting reductions in invested resources as indicators of productivity success demonstrated substantially larger divergence between productivity trajectories and cognitive-related usefulness outcomes.

These findings demonstrated that operational systems prioritising labour efficiency, energy-saving performance, operational simplification, and throughput-oriented productivity indicators frequently underestimated the long-term cognitive sacrifice associated with deteriorating indoor environmental quality.

Consequently, measurable productivity gains frequently coexisted with declining human cognitive functioning and worsening occupant-related usefulness outcomes.

Collectively, the physiological and cognitive findings demonstrated that productivity-oriented operational improvement frequently coexisted with increasing human-related sacrifice, declining cognitive performance preservation, and worsening occupant wellbeing.

More importantly, the findings demonstrated that confusing reduction in invested resources with genuine productivity improvement substantially intensified productivity–value decoupling across physiological protection, respiratory wellbeing, cognitive functioning, and broader occupant-related usefulness outcomes throughout the longitudinal investigation period.

Productivity–Value Decoupling

Longitudinal Productivity–Value Relationships: Longitudinal trajectory analysis demonstrated substantial divergence between productivity improvement and value-delivery improvement across buildings and intervention periods.

Several buildings demonstrated relatively proportional alignment between operational productivity and occupant-related usefulness outcomes. However, multiple buildings exhibited progressively worsening decoupling between these two trajectories over time.

Buildings classified as productivity–value aligned demonstrated relatively proportional improvement in operational efficiency, environmental quality, exposure protection, physiological stability, and occupant wellbeing.

In contrast, buildings classified as productivity–value decoupled demonstrated substantial improvement in operational productivity while occupant-related usefulness outcomes remained stagnant or deteriorated.

Importantly, the findings demonstrated that productivity–value decoupling existed even within buildings that did not strongly confuse reduction in invested resources with genuine productivity improvement.

Nevertheless, the degree of decoupling became substantially greater within buildings increasingly interpreting operational cost reduction, labour reduction, simplified operational procedures, and reduced environmental management activities as indicators of productivity success.

The most severe decoupling patterns emerged within buildings implementing aggressive operational cost-reduction strategies, reduced environmental monitoring frequency, ventilation scheduling optimisation, and simplified maintenance procedures.

In several cases, productivity improvement occurred simultaneously with worsening pollutant accumulation, increasing cumulative exposure burden, elevated physiological stress indicators, declining respiratory protection, and deteriorating cognitive performance preservation.

Buildings demonstrating the strongest emphasis on invested-resource reduction exhibited the largest divergence between productivity trajectories and value-delivery trajectories throughout the monitoring period.

In these buildings, productivity indicators improved by more than 30% while several occupant-related usefulness outcomes either remained relatively unchanged or deteriorated progressively over time.

Importantly, productivity–value decoupling frequently emerged gradually over time rather than immediately following operational intervention implementation.

This temporal delay proved scientifically important because organisations often continued reinforcing productivity-oriented operational strategies while usefulness-related outcomes progressively deteriorated beneath the visibility of conventional operational metrics.

Organisational Operational Behaviour: Operational records demonstrated progressively increasing organisational emphasis on intervention throughput, labour efficiency, operational cost reduction, maintenance speed, and energy-saving performance throughout productivity-oriented intervention periods.

Simultaneously, environmental monitoring frequency, occupant consultation activities, detailed airflow evaluation procedures, and exposure-related assessments frequently declined.

Buildings implementing the most aggressive productivity optimisation strategies demonstrated approximately 34.7% reduction in environmental monitoring frequency, 28.1% reduction in occupant-related evaluation activities, and 41.2% reduction in detailed ventilation assessment procedures.

These operational changes frequently improved measurable productivity indicators while simultaneously reducing organisational visibility into worsening environmental and occupant-related conditions.

Importantly, organisations demonstrating the strongest productivity–value decoupling were also the organisations most likely to operationally reinforce reductions in invested resources as evidence of productivity improvement.

This operational reinforcement progressively amplified the separation between measurable productivity gains and actual usefulness gained relative to invested resources.

The findings therefore demonstrated that productivity-oriented operational systems increasingly prioritised operationally visible efficiency indicators while progressively underweighting multidimensional usefulness-related outcomes and hidden occupant-related sacrifices.

More importantly, the findings demonstrated that confusion between invested-resource reduction and genuine productivity improvement substantially intensified productivity–value decoupling across real-world indoor air management systems operating under uncertainty, operational pressure, and competing organisational priorities.

Advanced Statistical and Causal Analysis

Longitudinal statistical modelling using generalised estimating equations demonstrated significant relationships among productivity-oriented operational changes, environmental deterioration, cumulative exposure burden, physiological stress indicators, cognitive decline, and worsening value-delivery trajectories across the 24-month investigation period.

Productivity indicators demonstrated only weak-to-moderate association with corresponding value-delivery indicators across repeated operational measurements.

Productivity trajectories frequently continued improving despite stagnation or deterioration in environmental quality, exposure protection, physiological wellbeing, and cognitive performance outcomes.

These relationships remained statistically significant after adjustment for occupancy variation, climatic fluctuation, building typology, baseline ventilation conditions, and temporal operational variation.

Difference-in-differences analysis demonstrated that buildings implementing productivity-oriented operational restructuring experienced significantly poorer occupant-related outcomes compared with matched buildings maintaining relatively stable environmental management conditions.

Buildings implementing ventilation reduction and maintenance simplification strategies demonstrated approximately 22.8% higher cumulative exposure burden, 17.9% greater physiological stress indicators, and 13.4% poorer cognitive-task performance relative to matched comparison buildings.

Productivity–value divergence further intensified following labour optimisation, operational cost reduction, reduced environmental monitoring, and ventilation scheduling interventions.

Machine learning clustering analysis identified four operational system categories comprising productivity–value aligned systems, weakly aligned systems, decoupled systems, and adversely coupled systems.

The strongest predictors of productivity–value decoupling included declining airflow effectiveness, reduced environmental monitoring frequency, elevated occupancy density, reduced occupant-related assessment activities, and aggressive operational cost-reduction strategies.

Decoupled and adversely coupled systems demonstrated continued productivity improvement despite stagnating or deteriorating environmental, physiological, and cognitive outcomes.

Bootstrapped longitudinal analyses involving 10,000 repeated resamples demonstrated strong stability across environmental, physiological, cognitive, and productivity–value trajectory models. Sensitivity analyses, cross-validation procedures, temporal stability analyses, instrumental variable analyses, and false discovery correction procedures were conducted to evaluate the robustness of the findings.

Collectively, these analyses demonstrated that the principal findings remained statistically significant across alternative productivity definitions, differing exposure thresholds, varying covariance structures, and alternative value-delivery weighting procedures.

Importantly, robustness analyses consistently demonstrated that productivity and value delivery did not remain perfectly aligned even when reductions in invested resources were not strongly misclassified as productivity improvement.

However, productivity–value decoupling became substantially greater when operational systems increasingly reinforced reductions in invested resources as indicators of productivity success under uncertainty, operational pressure, and competing organisational priorities.

Practical Interpretation for Real-World Context and Scientific Implications

The Phase II findings provided strong support for the alternative hypothesis (H_{12}) and rejected the null hypothesis (H_{02}). The investigation demonstrated that increases in productivity, defined as increases in output per unit of invested resources, were not reliably associated with proportional increases in value delivery under real-world indoor air management conditions.

Instead, productivity and value delivery became statistically decoupled across multiple operational contexts characterised by uncertainty, operational pressure, competing stakeholder priorities, and resource constraints.

Many organisations increasingly relied upon productivity-oriented indicators that were operationally visible, rapidly measurable, and organisationally rewarded.

These indicators included intervention throughput, labour efficiency, maintenance responsiveness, operational cost reduction, reduced staffing requirements, simplified operational procedures, and energy-saving performance. However, the findings demonstrated that these indicators frequently provided incomplete representation of actual occupant-related usefulness outcomes.

Several buildings demonstrated measurable productivity gains while simultaneously exhibiting deteriorating indoor environmental quality, increasing cumulative exposure burden, worsening physiological stress indicators, declining cognitive performance preservation, poorer airflow effectiveness, and worsening occupant comfort outcomes.

The findings, therefore, demonstrated that operational success defined primarily through output-oriented productivity indicators could coexist with substantial deterioration in occupant-related value delivery.

Importantly, productivity–value decoupling became substantially greater when organisations increasingly confused reductions in invested resources with genuine productivity improvement.

Under such conditions, reductions in operational expenditure, staffing levels, environmental monitoring activities, and intervention complexity were increasingly interpreted as evidence of productivity success even when measurable usefulness outcomes remained unchanged or progressively deteriorated.

More broadly, the investigation established productivity–value decoupling as a persistent operational phenomenon and provided the scientific foundation for Phase III, which subsequently examined whether AI-assisted cognitive capability enhancement could reduce productivity–value confusion and improve value-oriented judgement and decision-making.

Findings for Research Question 3 (Phase III):

Overview

Phase III examined how the use of an AI-based mobile decision-support framework, deployed on smartphones and tablets, enhanced practitioners' cognitive capability during indoor air management problem diagnosis and solving under conditions characterised by uncertainty, complexity, incomplete information, and competing stakeholder demands.

The findings demonstrated that practitioners using the AI-supported framework consistently outperformed practitioners continuing conventional operational practice across cognitive capability, judgement quality, decision quality, uncertainty interpretation, stakeholder integration capability, and action–value alignment.

Most importantly, the findings demonstrated that AI-assisted cognitive capability enhancement substantially reduced productivity–value confusion during indoor air management activities.

Practitioners using the framework demonstrated stronger ability to distinguish among productivity improvement, reduction in invested resources, usefulness-related improvement, and actual value delivery during judgement, decision-making, and operational action.

The behavioural and cognitive findings demonstrated that AI-assisted support reduced heuristic simplification, omission bias, attentional narrowing, and excessive reliance on operationally visible indicators such as intervention speed, maintenance throughput, operational cost reduction, labour reduction, and implementation simplicity.

Simultaneously, practitioners demonstrated substantially stronger integration of occupant-related usefulness outcomes, stakeholder consequences, exposure protection, comfort preservation, convenience, awareness, safety implications, and long-term environmental performance into operational reasoning and action processes.

The findings additionally demonstrated that practitioners using the AI-supported framework developed stronger reflective reasoning capability, improved uncertainty management, greater causal interpretation capability, and substantially better integration of indoor air quality and indoor air quantity considerations during operational evaluation activities.

These improvements strengthened practitioners' ability to evaluate how airflow effectiveness, pollutant dilution, exposure protection, and stakeholder-related usefulness outcomes interacted under real-world operational conditions.

Importantly, the findings demonstrated that AI-assisted cognitive capability enhancement improved judgement, decision-making, and operational actions that reduced the misclassification of reductions in invested resources as productivity gains and reduced the misinterpretation of productivity gains as evidence of proportional value-delivery improvement.

Overall, the findings provided strong evidence that AI-assisted cognitive capability enhancement improved value-oriented indoor air quality management problem diagnosis and solving under real-world operational conditions characterised by uncertainty, complexity, incomplete information, and competing stakeholder demands.

Experimental Indoor Air Management Scenarios Under Real-World Conditions

Real-world operational scenarios were evaluated across healthcare, educational, office, and residential buildings throughout the 12-month intervention period.

Approximately 4,860 indoor air management events were analysed, including ventilation inadequacy, transient pollutant exposure events, filtration adjustment conflicts, thermal discomfort complaints, maintenance constraints, energy-conservation interventions, uncertain pollutant source attribution, and delayed environmental feedback conditions.

Approximately 52.8% of events involved moderate operational uncertainty, while 28.6% involved high-uncertainty conditions characterised by incomplete environmental information, conflicting stakeholder demands, and delayed intervention outcome visibility.

Practitioners continuing conventional operational practice increasingly relied upon operationally visible indicators during high-pressure situations. Under high-uncertainty conditions, these practitioners prioritised intervention speed, maintenance throughput, operational simplicity, labour reduction, and operational cost reduction during approximately 68.4% of operational decision episodes.

In contrast, AI-assisted practitioners demonstrated substantially greater evaluation of occupant wellbeing, exposure reduction, comfort preservation, safety implications, awareness-related outcomes, and stakeholder-related consequences.

Importantly, AI-assisted practitioners demonstrated substantially stronger ability to distinguish among productivity improvement, reductions in invested resources, usefulness-related improvement, and actual value delivery.

Diagnostic agreement with independently reviewed multidisciplinary expert reference assessments reached 84.7 ± 6.8% among AI-assisted practitioners compared with 61.3 ± 9.7% among practitioners continuing conventional operational practice ($p < 0.001$).

The greatest differences emerged during situations involving conflicting stakeholder demands, uncertain pollutant source attribution, delayed environmental feedback, and incomplete environmental interpretation.

Under high-complexity conditions, omission bias frequency reached 17.8% among AI-assisted practitioners compared with 43.6% among conventional-practice practitioners ($p < 0.001$). Uncertainty consultation frequency was approximately 2.7 times greater among AI-assisted practitioners.

These practitioners demonstrated substantially greater willingness to seek environmental clarification, reassess assumptions, evaluate uncertainty-related limitations, and examine stakeholder-related consequences before making operational decisions.

Under conditions involving competing demands among energy conservation, operational expenditure reduction, occupant comfort, infection control, and exposure protection, value-oriented reasoning scores reached 82.4 ± 7.1 among AI-assisted practitioners compared with 57.2 ± 10.3 among control practitioners ($p < 0.001$).

During filtration optimisation conflicts, AI-assisted practitioners selected higher-protection interventions during 74.8% of operational scenarios compared with 39.7% among practitioners continuing conventional operational practice.

Collectively, these findings demonstrated that AI-assisted reasoning support substantially improved stakeholder integration capability, uncertainty management, and value-oriented operational reasoning under real-world indoor air management conditions.

AI-Supported Cognitive Capability Enhancement Design

Longitudinal Cognitive Capability Enhancement: The longitudinal intervention structure enabled evaluation of whether repeated interaction with the AI-supported framework progressively strengthened practitioner cognitive capability throughout the 12-month deployment period.

Baseline assessments conducted prior to intervention deployment demonstrated no statistically significant differences between intervention and control groups across diagnostic accuracy, uncertainty tolerance, reasoning quality, or operational decision capability. Mean baseline diagnostic accuracy reached 62.8 ± 8.1% within the intervention group and 63.4 ± 7.9% within the control group ($p = 0.74$).

However, substantial divergence emerged between the two groups throughout the intervention period. By Month 12, diagnostic accuracy increased to 86.9 ± 5.4% among AI-assisted practitioners while remaining comparatively stable at 65.7 ± 8.8% among control practitioners ($p < 0.001$).

Similarly, uncertainty interpretation quality increased by approximately 41.6% among AI-assisted practitioners compared with 8.4% among practitioners continuing conventional operational practice. Cognitive flexibility scores improved by 37.8% within the intervention group but only 6.9% within the control group.

Importantly, AI-assisted practitioners demonstrated progressively greater ability to evaluate incomplete environmental information, reassess operational assumptions, and integrate competing stakeholder-related consequences during uncertainty-intensive operational situations.

The findings demonstrated progressive strengthening rather than immediate short-term improvement alone. Bayesian hierarchical trajectory modelling showed that cognitive capability enhancement continued improving gradually across the intervention period rather than plateauing shortly after framework deployment.

This finding was scientifically important because it suggested that the AI-supported framework did not merely provide temporary task assistance. Instead, repeated reflective interaction with the framework progressively strengthened practitioner reasoning capability and uncertainty management under real-world operational conditions.

Productivity–Value Interpretation: One of the central objectives of Phase III involved examining whether AI-assisted reasoning support reduced productivity–value misclassification during indoor air management activities.

The findings demonstrated substantial reduction in productivity–value confusion among practitioners using the AI-supported framework. Productivity–value misclassification scores declined by approximately 46.8% among AI-assisted practitioners across the intervention period. In contrast, control practitioners demonstrated only marginal improvement of approximately 5.7%.

Under uncertainty-intensive operational conditions, conventional-practice practitioners continued demonstrating strong tendency to interpret operational cost reduction, intervention speed, labour reduction, and throughput improvement as evidence of proportional value-delivery improvement. AI-assisted practitioners demonstrated substantially greater differentiation between operational efficiency improvement and broader occupant-related usefulness outcomes.

This included substantially stronger evaluation of comfort, convenience, awareness, safety, exposure protection, and stakeholder-related consequences relative to operational sacrifices and invested resources incurred during intervention implementation.

AI-assisted practitioners demonstrated substantially greater ability to recognise that faster intervention completion, lower operational cost, reduced labour allocation, or improved maintenance efficiency did not necessarily correspond with proportional improvement in pollutant mitigation effectiveness, exposure protection, or occupant-related usefulness outcomes.

Consequently, AI-assisted practitioners were significantly less likely to incorrectly interpret operational efficiency improvement as evidence of successful value delivery when environmental protection and stakeholder-related usefulness outcomes remained inadequate.

The probability of productivity–value misclassification under high uncertainty conditions reached 0.64 among control practitioners compared with 0.23 among AI-assisted practitioners ($p < 0.001$).

Importantly, AI-assisted practitioners were significantly less likely to prematurely conclude that operational success had been achieved solely because intervention throughput, implementation speed, or operational efficiency indicators appeared favourable.

These findings demonstrated that the AI-supported framework substantially strengthened practitioners' ability to distinguish among productivity improvement, invested-resource reduction, usefulness-related outcomes, and actual value delivery during operational reasoning activities.

Development of the AI-Based Mobile Cognitive Capability Enhancement Framework

Framework Interaction and Usability: The AI-supported framework demonstrated high operational usability and sustained practitioner engagement throughout the intervention period. Mean daily framework interaction frequency reached 41.8 ± 9.6 interactions per practitioner, while average operational consultation duration reached 7.4 ± 2.3 minutes per operational event. Framework usage remained stable throughout the intervention period, indicating sustained practitioner engagement rather than temporary novelty-related interaction.

Practitioners reported particularly strong usability regarding uncertainty interpretation visualisation, stakeholder integration prompts, and reflective reasoning guidance functions. Real-time environmental interpretation dashboards were accessed during approximately 82.6% of operational intervention episodes.

The uncertainty interpretation module demonstrated especially high utilisation during operational situations involving uncertain pollutant source attribution and incomplete environmental measurements.

Under these conditions, practitioners increasingly consulted probabilistic confidence intervals, causal interpretation prompts, and uncertainty visualisation outputs before implementing operational interventions.

Importantly, the findings demonstrated that practitioners did not passively accept AI-generated recommendations. Instead, practitioners frequently revised, challenged, or further investigated framework recommendations prior to operational implementation.

Recommendation revision behaviour occurred during approximately 38.7% of operational decision episodes, indicating sustained practitioner cognitive involvement throughout the intervention period.

These findings demonstrated that the framework successfully functioned as a cognitive capability enhancement system rather than an automation-replacement system.

Explainable Artificial Intelligence: Explainable artificial intelligence architecture substantially improved practitioner trust, interpretability, and reflective engagement throughout the intervention period.

Practitioners demonstrated significantly greater trust in recommendations accompanied by transparent causal explanation pathways and uncertainty visualisation outputs compared with opaque recommendation outputs lacking interpretability support.

Recommendation acceptance rates increased from 58.4% during early deployment periods to 81.3% during later intervention stages following repeated exposure to explainable reasoning outputs.

Importantly, practitioners demonstrated substantially lower passive automation dependence compared with conventional automated decision-support systems reported in earlier literature. Passive recommendation acceptance without reflective evaluation occurred during only 12.4% of operational episodes among AI-assisted practitioners.

These findings demonstrated that explainable AI architecture substantially strengthened reflective cognitive engagement and reduced passive automation dependence during operational indoor air management activities.

Operationalisation of Cognitive Capability Enhancement

Diagnostic Accuracy and Decision Quality: Repeated cognitive capability assessments demonstrated substantial improvement among AI-assisted practitioners throughout the intervention period. Diagnostic accuracy agreement with multidisciplinary expert reference assessments increased progressively among AI-assisted practitioners across all building typologies.

The strongest improvements emerged during operational situations involving incomplete environmental information, uncertain pollutant source attribution, and conflicting stakeholder demands.

Decision quality scores reached 87.2 ± 6.1 among AI-assisted practitioners compared with 62.8 ± 9.8 among control practitioners by the end of the intervention period ($p < 0.001$).

AI-assisted practitioners additionally demonstrated significantly greater causal reasoning depth, uncertainty reflection, stakeholder integration capability, and long-term consequence evaluation during operational decision-making activities.

Operational action appropriateness scores also reached 85.6 ± 6.4 among AI-assisted practitioners. In comparison, practitioners continuing conventional operational practice achieved scores of 60.9 ± 9.7 ($p < 0.001$). The differences were particularly evident during ventilation adjustment, filtration optimisation, airflow redistribution, and exposure-mitigation intervention activities conducted under uncertainty-intensive conditions.

Heuristic Resistance and Cognitive Flexibility: Substantial differences emerged between intervention and control practitioners regarding heuristic dependence and cognitive flexibility.

Conventional-practice practitioners increasingly relied upon operational simplification heuristics during uncertainty-intensive operational conditions. In contrast, AI-assisted practitioners demonstrated substantially lower heuristic dependence and greater willingness to revise reasoning pathways in response to new environmental evidence.

Heuristic simplification frequency declined by approximately 39.8% among AI-assisted practitioners while remaining relatively stable among control practitioners. Similarly, adaptive probabilistic reasoning performance improved by approximately 34.6% among AI-assisted practitioners across the intervention period.

These findings demonstrated that AI-assisted reasoning support substantially strengthened practitioner resistance to heuristic oversimplification during cognitively demanding environmental interpretation activities.

Eye-Tracking: Eye-tracking analysis revealed major differences in attentional allocation patterns between intervention and control practitioners. Control practitioners increasingly allocated visual attention towards operationally visible indicators, including intervention speed metrics, cost-related variables, throughput indicators, and rapidly measurable operational outputs under uncertainty-intensive conditions.

In contrast, AI-assisted practitioners demonstrated significantly broader attentional allocation patterns incorporating occupant-related consequences, long-term exposure implications, environmental instability indicators, and stakeholder-related considerations.

Under high uncertainty conditions, fixation duration allocated towards occupant-related consequences reached 31.6% among AI-assisted practitioners compared with 14.8% among control practitioners ($p < 0.001$). Heat-map concentration analysis demonstrated substantially reduced attentional narrowing among practitioners using the AI-supported framework.

These findings demonstrated that AI-assisted reasoning support significantly altered practitioner attentional allocation patterns during operational decision-making activities.

Real-Time Behavioural and Environmental Data Integration

Behavioural Adaptation: Longitudinal behavioural interaction analysis demonstrated progressive behavioural adaptation among AI-assisted practitioners throughout the intervention period.

Practitioners increasingly engaged in reflective reasoning, uncertainty consultation, stakeholder evaluation, and causal interpretation during operational decision-making activities. Reflective reasoning duration increased by approximately 29.3% among AI-assisted practitioners over the intervention period, while premature closure behaviour declined substantially.

Importantly, behavioural adaptation remained evident even during operational episodes involving minimal direct framework prompting. This finding suggested that repeated AI-assisted reflective reasoning contributed to durable behavioural change rather than temporary externally dependent behavioural compliance alone.

Information-search behaviour similarly became progressively more multidimensional among AI-assisted practitioners. Intervention-group practitioners increasingly incorporated environmental, physiological, exposure-related, and stakeholder-related information streams during operational reasoning activities compared with control practitioners who remained substantially more reliant upon operationally visible indicators alone.

Environmental Interpretation: AI-assisted practitioners demonstrated substantially improved interpretation of transient pollutant events, airflow instability, cumulative exposure conditions, and delayed environmental consequence patterns throughout the intervention period.

During operational episodes involving rapidly changing pollutant concentrations, AI-assisted practitioners identified unstable environmental trajectories approximately 34.1% earlier than control practitioners. Similarly, intervention-group practitioners demonstrated significantly greater ability to detect emerging ventilation inadequacy before severe environmental deterioration occurred.

AI-assisted practitioners additionally demonstrated significantly greater ability to evaluate indoor air quality and indoor air quantity as distinct but interacting determinants of environmental system performance.

Practitioners increasingly recognised that increased airflow quantity alone did not necessarily correspond with proportional improvement in pollutant dilution effectiveness, exposure protection, airflow effectiveness, or broader occupant-related usefulness outcomes.

These findings demonstrated that integration of real-time environmental interpretation support substantially improved practitioner situational awareness and operational reasoning capability during dynamic indoor air management activities.

Physiological and Cognitive Outcome Measurements

Cognitive Performance: Objective cognitive assessments demonstrated substantial improvement among AI-assisted practitioners throughout the intervention period. Psychomotor vigilance performance improved by approximately 18.6% among intervention-group practitioners compared with 4.3% among control practitioners.

Stroop interference performance demonstrated approximately 22.7% improvement among AI-assisted practitioners, indicating substantially greater executive control and cognitive interference resistance under operational pressure.

Working memory performance assessed through N-back testing improved by approximately 17.9% among AI-assisted practitioners while remaining comparatively stable among practitioners continuing conventional operational practice.

Importantly, the strongest cognitive performance improvements emerged during uncertainty-intensive operational conditions involving competing stakeholder demands and incomplete environmental information.

These findings demonstrated that AI-assisted reasoning support substantially strengthened cognitive performance preservation during cognitively demanding operational activities.

Physiological Stress Regulation: Physiological monitoring demonstrated substantially improved adaptive stress regulation among AI-assisted practitioners throughout the intervention period.

Heart rate variability analysis demonstrated approximately 24.8% greater adaptive vagal regulation among intervention-group practitioners relative to control practitioners during uncertainty-intensive operational episodes.

Electrodermal activity similarly demonstrated substantially lower physiological arousal intensity among AI-assisted practitioners during cognitively demanding environmental interpretation activities.

Salivary cortisol concentrations declined progressively among intervention-group practitioners throughout the intervention period, while remaining comparatively elevated among control practitioners operating under equivalent operational conditions.

These findings demonstrated that AI-assisted cognitive capability enhancement not only improved reasoning quality but also strengthened physiological stress regulation during cognitively demanding operational activities.

Advanced Statistical and Causal Analysis

Longitudinal statistical modelling using generalised estimating equations demonstrated statistically significant improvement across cognitive capability, diagnostic accuracy, decision quality, stakeholder integration capability, uncertainty interpretation, and action–value alignment among practitioners using the AI-supported framework.

AI-assisted cognitive capability enhancement significantly predicted improved reflective reasoning, stronger causal interpretation, greater cognitive flexibility, and lower heuristic dependence throughout the intervention period.

These relationships remained statistically significant following adjustment for building typology, professional background, baseline diagnostic capability, occupancy variation, and environmental complexity.

Importantly, intervention-group practitioners progressively incorporated broader environmental, physiological, exposure-related, and stakeholder-related information streams into operational reasoning activities over time.

In contrast, practitioners continuing conventional operational practice remained substantially more dependent upon narrower operational indicators and simplified reasoning pathways under uncertainty-intensive conditions. Improvements in cognitive capability were additionally associated with progressively stronger alignment between operational decisions and occupant-related usefulness outcomes.

Structural equation modelling demonstrated strong mediation pathways linking AI-assisted cognitive capability enhancement, reflective reasoning quality, uncertainty interpretation capability, stakeholder integration, decision quality, and broader value-delivery outcomes. The primary mediation pathway demonstrated excellent statistical fit characteristics, including CFI = 0.96, RMSEA = 0.036, and SRMR = 0.039.

The findings demonstrated that the framework improved value-oriented operational performance primarily through strengthening human cognitive capability rather than through automation efficiency, task replacement, or accelerated operational execution alone.

Improvements in decision quality were strongly influenced by enhanced uncertainty evaluation, broader stakeholder consideration, and deeper causal interpretation during operational reasoning activities.

Difference-in-differences estimation demonstrated substantially greater longitudinal improvement among intervention-group practitioners relative to control practitioners across all principal outcome domains.

By the end of the intervention period, AI-assisted practitioners demonstrated substantially greater diagnostic accuracy, stronger long-term consequence evaluation, improved operational action appropriateness, lower omission bias frequency, and greater consistency between operational interventions and occupant-related protection objectives compared with practitioners continuing conventional operational practice.

Importantly, these improvements remained stable across sensitivity analyses, temporal stability testing, adversarial robustness testing, and alternative model specifications.

Collectively, the analyses demonstrated that AI-assisted cognitive capability enhancement produced durable improvement in reflective reasoning, uncertainty management, operational judgement, and value-oriented decision-making under complex real-world indoor air management conditions.

Practical Interpretation for Real-World Context and Scientific Implications

The Phase III findings provided strong support for the alternative hypothesis (H_{13}) and rejected the null hypothesis (H_{03}). The investigation demonstrated that the AI-based mobile decision-support framework had statistically significant positive effects on practitioners' cognitive capability, judgement, decision-making, and operational actions during indoor air management problem diagnosis and solving activities.

These improvements were observed under real-world conditions characterised by uncertainty, incomplete environmental information, competing stakeholder priorities, and dynamic operational pressures.

Most importantly, the findings demonstrated that AI-assisted cognitive capability enhancement improved how practitioners interpreted, evaluated, and responded to complex environmental situations rather than merely increasing operational speed or automating routine tasks.

Practitioners using the AI-supported framework became substantially more capable of identifying situations where apparently acceptable operational performance concealed underlying environmental instability, incomplete pollutant dilution, stagnant airflow zones, or inadequate occupant protection.

The findings additionally demonstrated that AI-assisted practitioners became more capable of distinguishing among operational efficiency improvement, reductions in invested resources, usefulness-related outcomes, and actual value delivery.

Consequently, the framework significantly reduced the tendency for practitioners to misclassify reductions in invested resources as productivity gains and to subsequently misinterpret productivity gains as proportional improvements in value delivery.

Practitioners using the framework also demonstrated improved uncertainty management during operational decision-making by evaluating environmental limitations, reconsidering assumptions, incorporating stakeholder-related consequences, and interpreting environmental conditions more cautiously before implementing interventions.

From a practical management perspective, the findings suggested that AI systems designed primarily to accelerate operational efficiency may unintentionally reinforce productivity–value confusion if they fail to support reflective reasoning and stakeholder-centred evaluation.

In contrast, explainable and cognitively supportive AI systems strengthened human judgement while preserving active practitioner involvement. More broadly, the findings established AI-assisted cognitive capability enhancement as a promising pathway for improving value-oriented indoor air management problem diagnosis and solving under complex real-world conditions.

………………… Chapter 5 ……………………

After completing her PhD, Amina expected life to become clearer. For years, she had imagined that successfully defending her doctoral research would finally give her emotional closure after the confusion, frustration, and intellectual conflict that had shaped much of her young adulthood. Instead, the opposite happened. The deeper she reflected upon the implications of her findings, the more unsettling the world around her became.

Her doctoral research had already generated substantial empirical evidence relating to judgement and decision-making under uncertainty-intensive conditions. The findings demonstrated that practitioners operating under conditions involving uncertainty, environmental complexity, incomplete information, competing stakeholder priorities, operational pressure, and heterogeneous human needs increasingly gravitated toward operationally visible indicators during judgement and decision-making activities. This occurred because such indicators often felt psychologically safer, easier to defend organisationally, and easier to interpret under pressure.

What disturbed her now was no longer whether the cognitive flaw existed. Her research had already confirmed that it did. The deeper challenge involved understanding how societies and institutions could realistically operate within increasingly complexity-intensive environments without gradually sacrificing human value delivery beneath operational optimisation pressures.

The implications disturbed her profoundly because she realised the problem extended far beyond indoor air management alone. The flaw appeared deeply embedded within the way modern society increasingly interpreted success itself.

Several months after graduation, Amina accepted a postdoctoral research position within a multidisciplinary healthy buildings institute attached to one of the leading technological universities in the country.

As her research influence expanded over the following years, she gradually progressed into a senior research and academic role within the institute, leading several major projects relating to healthy buildings, indoor air management, and AI-assisted cognitive capability enhancement systems.

The institute itself reflected many of the contradictions she had spent years studying. The research centre proudly promoted innovation, sustainability, intelligent infrastructure, and human-centred environments.

Giant digital displays across the building showcased real-time energy efficiency statistics, carbon reduction achievements, operational optimisation indicators, and smart-building performance dashboards.

Yet behind the polished institutional image, many researchers quietly struggled with exhaustion, anxiety, emotional fatigue, and growing pressure to continuously produce measurable academic output. Some researchers spent nights sleeping inside laboratories before major project deadlines.

Others quietly developed health problems while trying to maintain impossible publication expectations, grant targets, teaching responsibilities, and industrial collaboration commitments simultaneously.

Even informal conversations inside the institute increasingly revolved around measurable output: publication count, citation performance, grant acquisition success, industry funding, implementation speed, and institutional rankings. Amina increasingly noticed that the same cognitive tensions she had studied within indoor air management systems were quietly unfolding inside academia itself.

At first, Amina remained mostly silent while observing the environment around her carefully. She had learnt over the years that many intelligent systems did not fail dramatically at the beginning. Instead, they gradually conditioned people to normalise contradictions that would once have appeared deeply disturbing.

During meetings, she noticed how discussions about human wellbeing frequently became secondary whenever financial constraints, implementation speed, operational efficiency, or measurable performance indicators entered the conversation.

Researchers who produced visible outputs quickly received praise, funding opportunities, and institutional visibility. Meanwhile, individuals raising difficult questions about long-term human consequences, stakeholder complexity, or cognitive burden were often described as “slowing progress,” “overcomplicating implementation,” or “lacking practicality.”

The contradiction fascinated and unsettled her simultaneously because many people inside the institute genuinely cared about improving human wellbeing. Yet the operational systems governing the institution continuously rewarded measurable visibility more strongly than multidimensional human impact because visible indicators remained easier to evaluate, compare, defend, and manage organisationally.

The contradiction became even more visible during her first major industry collaboration project after completing her PhD. A large property development company invited the research institute to help optimise the environmental management systems across several newly developed smart office buildings.

Publicly, the company promoted the buildings as future-ready human-centred workplaces designed to support health, sustainability, comfort, and productivity simultaneously. The buildings themselves looked stunning. Automated façades adjusted dynamically according to sunlight conditions.

AI-controlled ventilation systems continuously optimised airflow patterns and energy usage in real time. Environmental dashboards displayed beautiful visualisations of operational performance across giant digital screens inside building lobbies. Investors praised the buildings enthusiastically during public launch events.

Media outlets described the developments as symbols of the future intelligent city where technology, sustainability, and human wellbeing would supposedly coexist harmoniously through advanced optimisation systems. However, once Amina began interviewing occupants quietly, a very different picture emerged.

Employees repeatedly described feeling mentally drained after spending long hours inside the buildings. Some complained about headaches that became worse toward the afternoon. Others described unusual cognitive fatigue despite the buildings maintaining technically acceptable environmental conditions according to standard operational measurements.

Several workers explained that they increasingly struggled to concentrate during cognitively demanding tasks, even though the organisation itself continued celebrating operational performance improvements.

More disturbingly, different stakeholder groups interpreted the building entirely differently depending on their priorities. Senior executives praised energy savings and operational efficiency.

Financial managers focused on maintenance cost reductions. Sustainability consultants celebrated reduced carbon emissions. Yet many occupants increasingly felt emotionally disconnected from the spaces they inhabited daily.

Some employees even admitted privately that although the buildings looked technologically impressive, they no longer felt psychologically comfortable spending long, uninterrupted hours inside them. A few described the environment as strangely “sterile” or “emotionally cold,” even though they could not explain the feeling scientifically.

What disturbed Amina most was not merely the existence of competing stakeholder priorities but how complexity itself increasingly pushed people toward simplified interpretations of success.

Each stakeholder group focused primarily upon the indicators most psychologically accessible to them because no individual could comfortably process the full multidimensional complexity unfolding simultaneously across the system.

The finance department viewed the building through operational expenditure. Engineers focused on system stability and performance compliance. Sustainability officers prioritised carbon reduction metrics. Occupants cared about comfort, cognitive clarity, environmental confidence, emotional wellbeing, and their ability to function effectively throughout long working hours.

The problem was not that any single stakeholder was entirely wrong. The deeper problem was that modern operational environments had become so complex that people increasingly reduced reality to whichever indicators felt most measurable, defensible, emotionally manageable under pressure, or most aligned with their own interests.

As a result, operationally visible forms of success increasingly dominated organisational reasoning because they reduced the psychological discomfort created by complexity itself.

One evening after a particularly tense stakeholder meeting, Amina sat alone inside the building’s observation room overlooking the illuminated city skyline. Rain pressed softly against the glass façade while environmental dashboards continued glowing quietly across nearby screens.

The meeting earlier that afternoon had become emotionally exhausting. Senior management wanted immediate operational recommendations capable of preserving energy efficiency achievements while reducing occupant complaints without significantly increasing operational expenditure.

The engineering consultants insisted the building systems were technically functioning within acceptable standards. Human resource representatives worried about increasing employee dissatisfaction. Sustainability officers feared that relaxing optimisation settings might negatively affect the company’s public environmental image. Every stakeholder entered the discussion carrying legitimate concerns, yet the competing priorities continuously collided against one another.

Nobody inside the room appeared malicious or intentionally irresponsible. Yet despite the intelligence, experience, and professional expertise present during the discussion, meaningful consensus remained painfully difficult because every proposed intervention improved certain forms of value while simultaneously creating sacrifices elsewhere across the system.

For several moments, Amina simply stared silently at the environmental dashboards. Unlike earlier periods of her life, she was no longer searching for evidence that the problem existed.

Her doctoral research had already generated substantial empirical findings validating much of the cognitive framework proposed in the professor's work she had encountered online years earlier, before beginning her PhD. The existence of the cognitive flaw was no longer the central question confronting her.

What unsettled Amina now was something far more difficult. Her research had already demonstrated that the AI-assisted cognitive capability enhancement framework could strengthen reflective reasoning, stakeholder integration, and value-oriented judgement during real-world indoor air management activities. These activities were characterised by uncertainty, complexity, operational pressure, and heterogeneous stakeholder needs. However, successful validation did not guarantee that institutions adopting the framework would preserve its original human-centred purpose over time.

As governments, universities, healthcare institutions, and engineering organisations increasingly expressed interest in implementing the framework, Amina became increasingly concerned that the system itself might gradually be absorbed into the very optimisation culture it had originally been designed to address.

If organisations eventually prioritised measurable efficiency gains, implementation speed, institutional visibility, or performance metrics more strongly than genuine human value delivery, the framework itself risked gradually becoming reduced into another operational optimisation mechanism. Under such conditions, the framework could lose its original purpose of strengthening human-centred judgement under complexity-intensive conditions.

That concern gradually became one of the defining tensions shaping the next phase of her academic career. Her work increasingly shifted toward protecting the philosophical and human-centred integrity of the framework as adoption expanded across industries, institutions, and intelligent operational systems.

At first, Amina believed the organisations adopting her framework genuinely understood its purpose. Several hospitals, universities, corporate facilities, and intelligent building companies publicly described the system as a breakthrough in human-centred operational reasoning.

International conferences praised the framework enthusiastically. Government agencies invited her to participate in advisory panels on future intelligent infrastructure systems. For a brief period, Amina felt cautiously hopeful that institutions were finally beginning to take the relationship between operational optimisation and human value delivery seriously.

Then the reports began arriving. One of the earliest warning signs emerged from a large multinational property management company that had implemented a modified version of her AI-assisted cognitive capability enhancement system across several commercial office developments.

During the initial rollout, the company publicly emphasised the framework's human-centred philosophy, reflective reasoning capability, and stakeholder integration features. However, over time, organisational priorities gradually shifted.

Senior management became increasingly interested in how the system could improve operational speed, reduce environmental management labour requirements, accelerate maintenance decisions, and standardise decision-making processes across multiple facilities.

The change appeared subtle at first. Several reflective prompts designed to encourage deeper stakeholder evaluation were quietly removed because some managers considered them "operationally inefficient." Environmental uncertainty analysis modules were simplified to accelerate response speed during maintenance activities.

Human-centred contextual reflection components became increasingly bypassed whenever they delayed implementation timelines. Eventually, the company began marketing the system primarily as an "AI operational optimisation platform" rather than a cognitive capability enhancement framework.

When Amina first reviewed the revised implementation reports, she felt physically unsettled. The framework was beginning to become exactly what she had feared. Several months later, occupant complaints across some of the buildings quietly began increasing again. Employees described growing cognitive fatigue, environmental discomfort, declining concentration, and emotional exhaustion during extended working hours.

Yet internally, the organisation continued celebrating improved operational response efficiency, reduced management costs, and faster environmental decision throughput. The contradiction horrified Amina because it mirrored the same societal flaw the framework had originally been designed to address.

For several nights, she barely slept. What disturbed her most was not merely that organisations were misusing the system. The deeper problem was that the distortion appeared psychologically natural under institutional pressure.

Once organisations became financially and operationally accountable to measurable performance indicators, the framework itself gradually became absorbed into the same optimisation logic governing the surrounding system.

That realisation changed the direction of her work again. Amina began redesigning the framework architecture itself to make human-centred reflective reasoning more difficult to bypass operationally.

Rather than allowing organisations to selectively disable stakeholder complexity modules or uncertainty interpretation features, later versions of the framework increasingly integrated reflective evaluation directly into the core operational reasoning pathway.

That realisation changed the direction of her work again. Amina began redesigning the framework architecture itself to make human-centred reflective reasoning more difficult to bypass operationally.

Rather than allowing organisations to selectively disable stakeholder complexity modules or uncertainty interpretation features, later versions of the framework increasingly integrated reflective evaluation directly into the core operational reasoning pathway.

Importantly, the framework operated as a continuously updated cloud-connected AI platform used across participating organisations. This meant that major architectural revisions, reflective safeguards, and value-integrity protocols introduced by Amina's research team could be progressively deployed into organisational systems through scheduled software updates rather than requiring institutions to rebuild their entire operational infrastructure from the beginning.

However, the process remained far more complicated than simple software upgrading alone. Many organisations had already customised earlier versions of the framework according to their own operational priorities, internal workflows, financial constraints, and institutional preferences.

As a result, some companies resisted certain updates because the newer versions reduced their ability to bypass reflective evaluation processes during time-sensitive operational decisions. Several organisations argued that the additional human-centred safeguards slowed implementation speed, complicated workflow efficiency, and increased operational friction under high-pressure conditions.

To address this, Amina and her research team gradually redesigned the platform using layered implementation architecture. Core human-centred reasoning functions, stakeholder evaluation safeguards, uncertainty interpretation mechanisms, and value-integrity monitoring systems became deeply embedded within the platform's foundational reasoning engine itself.

As a result, organisations found it far more difficult to selectively deactivate those features without fundamentally compromising the functionality and stability of the system. At the same time, organisations still retained limited flexibility to customise operational workflows according to their specific environmental, financial, and institutional needs.

Amina understood that if the framework became excessively rigid, organisations might reject adoption entirely. Yet if the system remained too operationally flexible, institutions could gradually strip away the very reflective mechanisms designed to protect human value delivery in the first place. Balancing those competing realities became one of the most difficult and politically sensitive aspects of her post-PhD career.

To further protect the framework from gradual institutional distortion, Amina later introduced what became internationally known as “value integrity protocols.” These protocols continuously monitored whether organisations were increasingly using the system primarily for operational optimisation while neglecting the human-centred value-delivery objectives the framework had originally been designed to protect.

If operational efficiency gains increasingly diverged from occupant wellbeing, cognitive performance, environmental confidence, or stakeholder-related outcomes, the system automatically triggered reflective reassessment requirements rather than allowing optimisation pathways to continue unquestioned indefinitely.

The introduction of the protocols generated significant international controversy. Several industry leaders accused Amina of embedding excessive ethical and operational constraints into systems that organisations needed to keep commercially competitive under high-pressure conditions. Others argued that the framework was becoming “too philosophically restrictive” for real-world operational environments.

Amina nevertheless refused to compromise. During one particularly controversial international conference, she openly stated: “A system designed to protect human value should not be evaluated solely according to how efficiently it helps organisations optimise themselves.”

The statement divided professional communities sharply. Some industry groups criticised her publicly, while many younger engineers, healthcare professionals, architects, educators, and researchers increasingly supported her position because they had already witnessed how easily intelligent systems became absorbed into optimisation culture once measurable performance incentives began dominating implementation environments.

Over time, however, the growing tension surrounding Amina’s work gradually began producing something unexpected. As more organisations implemented the framework across real-world operational environments over extended periods, a clearer picture started emerging.

Institutions that preserved the framework's reflective reasoning safeguards and human-centred evaluation structures consistently demonstrated stronger long-term outcomes across multiple areas.

Occupants within those environments generally reported better wellbeing, stronger cognitive functioning, and greater environmental confidence over time. The organisations themselves also demonstrated improved long-term stability, stronger staff retention, better learning performance, improved healthcare recovery conditions, and greater operational resilience during crisis situations.

Several hospitals reported that healthcare workers functioning within environments managed using the full framework experienced lower cognitive exhaustion and improved decision confidence during high-pressure clinical operations.

Educational institutions adopting the framework observed improvements in student concentration, emotional regulation, and long-term learning engagement despite only moderate increases in operational expenditure.

Some corporate organisations unexpectedly discovered that employees working inside environments prioritising genuine value delivery rather than aggressive optimisation alone demonstrated stronger long-term productivity sustainability, reduced burnout-related absenteeism, and improved organisational trust over time.

Gradually, even some of Amina's earlier critics began reconsidering their positions. What many institutions initially interpreted as "operational friction" increasingly revealed itself to be a form of cognitive protection against oversimplified reasoning under complexity-intensive conditions.

Organisations slowly realised that rapid optimisation without sufficient reflective evaluation often generated hidden downstream consequences that later became far more expensive financially, operationally, and humanly to address.

The turning point came nearly fifteen years after Amina completed her PhD. An independent international review consortium later analysed large-scale implementation outcomes across healthcare facilities, universities, intelligent commercial buildings, and public infrastructure systems.

The consortium subsequently released a landmark report comparing organisations that preserved the framework's human-centred reflective architecture with organisations that had heavily simplified the framework for operational convenience. The findings attracted global attention.

Institutions preserving the reflective safeguards consistently demonstrated stronger long-term value delivery across multidimensional performance indicators.

While some highly simplified systems initially achieved faster operational throughput and lower short-term expenditure, many later experienced worsening occupant dissatisfaction, cognitive fatigue complaints, stakeholder distrust, organisational instability, and declining long-term operational resilience.

By contrast, organisations retaining the framework's human-centred reasoning architecture generally demonstrated more stable long-term performance across both operational and human-related outcomes simultaneously.

The report changed the global conversation permanently. For the first time, large-scale longitudinal evidence demonstrated that protecting human-centred reflective reasoning under uncertainty, complexity, and heterogeneous stakeholder conditions was not merely ethically desirable. It also strengthened long-term organisational sustainability itself.

The findings significantly weakened the earlier criticism that Amina's framework represented impractical philosophical idealism incompatible with real-world operational environments.

International policy bodies gradually began revising healthy building guidelines, intelligent infrastructure governance frameworks, and AI-assisted environmental management standards accordingly. Several engineering accreditation systems introduced new competency requirements relating to reflective reasoning, stakeholder integration, uncertainty interpretation, and value-oriented judgement under complexity-intensive operational conditions.

Universities increasingly redesigned engineering curricula to strengthen students' cognitive capability for navigating multidimensional real-world environments rather than training them primarily for simplified optimisation tasks alone.

Perhaps most importantly, the culture surrounding intelligent systems themselves slowly began shifting. Earlier generations of AI-assisted operational systems had largely been evaluated according to speed, automation capability, labour reduction, and optimisation efficiency.

However, newer systems increasingly incorporated human-centred reflective architecture directly into their foundational design principles. AI was no longer viewed merely as a tool for accelerating operational performance. It increasingly became recognised as a system capable of supporting deeper human judgement under conditions where complexity, uncertainty, and competing stakeholder realities could easily overwhelm unaided reasoning.

As Amina's influence across healthy buildings, indoor air management, and AI-assisted cognitive capability enhancement continued expanding internationally, her role within the university gradually evolved far beyond her original postdoctoral appointment. What began as a research-focused position inside the healthy buildings institute eventually developed into a joint research and faculty appointment after her teaching methods and cognitive capability frameworks began attracting growing attention across the university.

Over the following years, she progressed into associate professor, later became director of the institute’s newly established Centre for Value-Oriented Intelligent Environmental Systems, and eventually rose to full professorship as her work increasingly influenced international engineering practice, healthy building governance, and AI-assisted operational reasoning systems.

Within those evolving roles, Amina increasingly transformed not only her research agenda but also her teaching philosophy. Her classrooms gradually became known across the university for intellectually and emotionally intense discussions rather than conventional technical lectures alone.

Students entering her modules quickly realised they would not simply memorise formulas or optimisation strategies. Instead, they would confront realistic scenarios involving conflicting stakeholder needs, incomplete environmental information, uncertain pollutant source attribution, delayed health consequences, financial pressure, organisational politics, and human psychological complexity.

During one particularly memorable lesson, Amina presented students with a realistic scenario involving a school building experiencing increasing complaints about fatigue, headaches, poor concentration, and declining student attentiveness despite technically acceptable environmental measurements.

Different stakeholders interpreted the situation differently. School administrators feared reputational damage and increasing operational costs. Teachers worried about declining learning performance. Parents demanded immediate action to protect their children. Maintenance teams insisted all systems were functioning correctly according to technical standards. Sustainability officers opposed increasing ventilation rates because of energy penalties. Financial officers wanted the cheapest intervention possible.

The classroom became emotionally chaotic. Students initially argued aggressively for simplified technical solutions based on whichever variables they personally prioritised. However, as discussions deepened, many gradually became uncomfortable after realising how difficult meaningful judgement became once complexity, uncertainty, delayed consequences, stakeholder heterogeneity, and incomplete information interacted simultaneously.

Some students later admitted the exercise permanently changed the way they understood engineering because it forced them to recognise that real-world problem-solving often involved navigating competing forms of value rather than optimising isolated variables alone.

Amina increasingly viewed such classroom discomfort as educationally necessary because she believed future practitioners needed to develop the cognitive capability to remain reflective under pressure rather than collapsing immediately into oversimplified operational reasoning pathways.

Meanwhile, the AI-assisted cognitive capability enhancement framework she had developed and refined over the years continued evolving operationally across real-world implementation environments.

Over time, Amina's research centre became internationally recognised for pioneering AI-assisted cognitive capability enhancement systems within healthy building and indoor air management practice.

Unlike conventional AI platforms focused primarily on automation efficiency, predictive optimisation, or operational acceleration, her systems were specifically designed to strengthen reflective reasoning under complexity-intensive conditions involving uncertainty, competing stakeholder priorities, incomplete information, and operational pressure.

The systems continuously exposed practitioners to hidden stakeholder impacts, long-term human consequences, uncertainty levels, environmental context variability, and competing operational priorities during decision-making activities.

Despite growing international recognition, Amina remained emotionally cautious about success itself. She understood too well how visible achievement could quietly conceal deeper problems underneath.

Many nights, long after conferences ended and public lectures concluded, she still found herself remembering Daniel, the competition hall, and the emotionally disturbing moment when operational success and human wellbeing visibly moved in opposite directions before her eyes for the first time.

Decades later, after becoming one of the world's leading authorities on value-oriented indoor air management and cognitive environmental systems, Amina returned quietly one evening to the same university laboratory where the adaptive learning booth had once been constructed during her student competition years.

The laboratory had changed enormously since then. Advanced AI systems now filled many research spaces. Younger students moved rapidly between experimental workstations while discussing machine learning, environmental simulation, and cognitive analytics. Yet standing alone near the corner where the old prototype once stood, Amina suddenly felt overwhelmed by the strange emotional continuity connecting her entire life.

Everything had started there. Not with technology alone. Not with optimisation alone. But with a disturbing question society itself increasingly avoided asking: What happens when intelligent systems become better at optimising operational performance than protecting the human beings living and operating inside them?

As she stared quietly across the laboratory, Amina realised that her life's work had never truly been about rejecting optimisation itself. Processes and systems still required efficiency. Buildings still needed sustainability. Organisations still required operational stability under uncertainty-intensive conditions.

The deeper issue was whether society retained enough cognitive capability to continuously evaluate whether optimisation genuinely improved human value delivery across diverse stakeholder realities rather than merely improving visible operational indicators alone.

Outside the laboratory windows, the city skyline still glittered with extraordinary beauty beneath the night sky. Yet unlike the young woman who once stared at the same city years earlier, feeling emotionally helpless, Amina now understood something profoundly important.

The future of society would not depend solely upon how intelligent its systems became. It would also depend upon whether human beings remained capable of thinking deeply enough under uncertainty, complexity, and heterogeneous stakeholder pressures to ensure those systems continued protecting human value rather than quietly consuming it.

………………… Chapter 6 ……………………

Amina's transformation did not remain confined to her research, teaching, or professional leadership within intelligent environmental systems and healthy building governance.

Over time, the same shift in thinking that had fundamentally changed how she approached uncertainty, complexity, stakeholder heterogeneity, and value-oriented judgement in professional environments gradually began reshaping how she related to people in her private life as well.

The transformation did not arrive dramatically. Instead, it emerged quietly through small behavioural shifts that accumulated slowly across many years of marriage, parenthood, friendships, and everyday interactions.

Her husband, Idris, who had known her since the years before her PhD, began noticing the changes long before Amina fully recognised them herself. At first, the differences appeared almost insignificant. Amina became slower to react during emotionally charged conversations. She paused more often before responding. Situations that would previously have triggered immediate explanation, interpretation, or correction now unfolded more slowly. Idris noticed that she had become more comfortable sitting inside unresolved conversations without instinctively trying to force immediate closure.

Earlier in life, especially during the intense years when her academic responsibilities and international influence were expanding rapidly, Amina often approached personal situations with the same cognitive habits that shaped her early understanding of engineering systems.

When problems emerged, she instinctively felt responsible for understanding, stabilising, or resolving them quickly. Although her intentions were usually good, this sometimes caused her to respond more strongly to her interpretation of a situation than to the emotional reality experienced by the people around her.

During the earlier years of their marriage, whenever Idris expressed frustration or emotional exhaustion, Amina often interpreted the situation as a problem requiring analysis or correction. She instinctively searched for causes, proposed practical solutions, or reorganised circumstances to improve the situation. Yet she did not always recognise that sometimes Idris simply wanted emotional presence rather than operational problem-solving.

There were evenings when Idris returned home emotionally overwhelmed after filming difficult documentary scenes involving poverty, loneliness, or social decline. He would sit quietly at the dining table, trying to describe the emotional weight of what he had witnessed throughout the day. Amina, meanwhile, often responded by analysing workload structures, suggesting ways to reduce stress, or discussing how he might better organise future projects.

At the time, she genuinely believed she was helping. Only years later did she fully realise that many of those moments had not required immediate solutions at all. Sometimes Idris simply wanted someone willing to sit beside him emotionally without immediately trying to reorganise reality itself.

That realisation gradually changed how Amina approached conversations and emotional tension within her personal life. The more years she spent researching uncertainty, incomplete information, delayed consequences, stakeholder heterogeneity, and multidimensional value delivery professionally, the more she began recognising similar patterns within ordinary human relationships as well.

Over time, she became less quick to defend herself, explain situations, or rush toward immediate solutions during difficult conversations. Instead, she started listening more carefully and asking questions to better understand what others were truly feeling before deciding how to respond.

This did not mean she became passive or indecisive. She gradually realised that thoughtful reflection and responsible action were not opposites. Some situations still required timely decisions, intervention, guidance, or boundaries. The difference was that she increasingly tried to ensure her actions emerged from deeper understanding rather than from anxiety, impatience, or the discomfort of uncertainty itself.

This shift significantly changed the emotional atmosphere within her marriage. Earlier in their relationship, disagreements sometimes escalated because conclusions were reached too quickly. Idris would raise an emotional concern.

Amina would instinctively interpret the issue and respond through explanation, justification, or problem-solving logic. Although she believed she was helping, Idris occasionally felt that the emotional essence of what he was trying to communicate disappeared beneath analysis and reasoning.

As Amina changed over the years, however, Idris increasingly noticed that she was listening differently. She no longer listened merely to formulate responses or identify solutions. She listened to understand the deeper context surrounding what another person was experiencing.

There were moments when Idris would stop speaking halfway through a difficult conversation simply because he realised Amina was no longer trying to “win” the discussion intellectually or immediately fix the situation. Instead, she was trying to understand him.

That difference gradually transformed the emotional structure of their relationship itself. Conversations became calmer, slower, and less defensive. Conflicts became less focused on proving perspectives and more centred around developing shared understanding.

Over time, this created deeper emotional trust between them because Idris increasingly felt not only intellectually respected by Amina, but emotionally heard as well.

The transformation also gradually changed how Amina related to her children. During the earlier years of motherhood, especially while balancing growing international responsibilities, institutional leadership, research demands, and constant travel, Amina sometimes approached parenting with the same efficiency-oriented mindset shaping many other areas of her life.

When her children struggled emotionally, academically, or socially, her instinct was often to immediately identify the problem, organise a solution, and help them recover quickly.

When their eldest daughter began struggling academically during adolescence, Amina initially responded by reorganising study schedules, arranging additional academic support, and trying to optimise the situation quickly because she genuinely wanted to help. Yet over time, she gradually realised that the deeper issue was not academic performance itself.

Her daughter had quietly become overwhelmed by anxiety, emotional pressure, and fear of disappointing expectations surrounding success. The more intensely Amina attempted to improve the situation operationally, the more emotionally pressured her daughter began feeling internally.

That discovery unsettled Amina deeply because she suddenly recognised traces of the same optimisation culture she had spent decades criticising professionally, quietly appearing within her own parenting.

From that point onward, her approach gradually changed. Instead of immediately focusing on visible performance outcomes or behavioural correction, she became more attentive to the emotional realities underneath situations themselves. She became more patient in allowing her children to express confusion, frustration, disappointment, or uncertainty without immediately redirecting conversations toward improvement strategies.

At the same time, she also recognised that good parenting did not mean avoiding action indefinitely while waiting for children to eventually solve everything emotionally themselves.

Some situations still required guidance, boundaries, intervention, or decisive action. The difference was that she increasingly tried to ensure those actions emerged from understanding rather than from fear, urgency, or discomfort surrounding uncertainty.

Over time, these changes gradually transformed the emotional atmosphere within the family. Her children increasingly felt less pressured to constantly appear capable, composed, or successful around her. Conversations became more open, less defensive, and emotionally safer because they increasingly felt understood rather than managed.

As her children entered adulthood, Amina began noticing another unexpected consequence of her transformation. Her children themselves gradually became more reflective in how they approached relationships, uncertainty, conflict, and responsibility within their own lives.

They learnt that uncertainty did not always need to be feared or eliminated immediately. At the same time, they also learnt that uncertainty should not become an excuse for avoiding responsibility or endlessly postponing necessary action.

Through observing both their mother’s earlier mistakes and later transformation, they gradually developed a healthier balance between thoughtful reflection and timely action within their own personal lives.

As the years passed, Amina increasingly realised that the optimisation tendencies she had once identified within engineering systems and intelligent operational environments were deeply embedded throughout ordinary human behaviour and modern social culture more broadly.

In workplaces, universities, governments, friendships, marriages, and parenting, she observed how easily people gravitated toward whatever appeared fastest, most measurable, operationally defensible, or psychologically reassuring under pressure.

Yet rather than becoming cynical about this reality, Amina gradually developed a quieter sense of responsibility toward helping people remain reflective enough to recognise those tendencies within themselves.

By the later years of her life, she increasingly understood that the most meaningful outcome of her transformation was not merely the international influence of her research framework or the institutional systems shaped by her work.

It was the way the transformation had gradually changed how she listened, how she understood people, how she responded to uncertainty, and how she learnt to protect forms of human value that could never be fully captured through operational indicators alone.

In this sense, Amina's transformation ultimately became holistic. The same principles shaping her professional philosophy gradually reshaped her marriage, her parenting, her relationships, and her understanding of human life itself. Reflection before reaction. Understanding before conclusion. Human value before operational convenience.

Over time, these principles became not merely ideas within her research, but foundations guiding how she lived, related to others, raised her children, sustained her marriage, and understood the world around her. **The End!**